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Comparative Tests of Crushed Stone and Gravel Concrete in New Jersey[1]

Report on Cooperative Tests Conducted by the New Jersey State Highway Commission and The U. S. Bureau of Public Roads

Reported by F. H. JACKSON, Engineer of Tests, Division of Tests, U. S. Bureau of Public Roads

DURING the summer of 1926 the New Jersey State Highway Commission, working in cooperation with the Bureau of Public Roads, conducted a series of concrete tests at the Trenton laboratory of the commission, for the purpose of determining the relative quality and economy of concrete paving mixtures in which 13 different gradations of crushed stone (trap) and gravel were used as coarse aggregate. The investigation involved the making and testing of approximately 150 concrete beams, 8 by 8 by 48 inches in size and 250 concrete cylinders 6 by 12 inches in size.

This report describes in order (1) the various reasons which led up to the investigation, (2) the procedure followed, (3) the results secured, and (4) the conclusions reached, and makes certain recommendations relative to the application of these results. It should be borne in mind that this series of tests was initiated for the purpose of studying the relative merits of two different types of coarse aggregate produced under certain conditions. The results can therefore be considered as applicable only to the same kinds of material, produced in a similar manner. In order to make possible the drawing of more general conclusions as to the effect of type and gradation of coarse aggregate upon the quality of concrete a series of tests has been started at the Arlington laboratory of the bureau. These tests are similar to those described here but involve seventeen types of coarse aggregate instead of two. It is anticipated that conclusions suitable for general application will be justified by these tests, but in the meantime those presented here should not be considered as having any application beyond the particular conditions involved.

THE CONCLUSIONS drawn from these tests should not be interpreted as indicating that crushed stone as a type is superior to gravel as coarse aggregate for cement concrete pavements, but only as indicating that for the particular conditions and kinds of materials involved, concrete in which crushed trap rock was used showed an average flexural strength approximately 12 per cent higher than similar concrete in which gravel was used.

Tests now in progress at the Arlington Laboratory using 17 different coarse aggregates give preliminary indications that materials similar to those used in this investigation will give similar results, but also that the characteristics of the particular aggregate used may be fully as important as the type of material to which it belongs.

Reasons Leading to Investigation Discussed

The practice followed in New Jersey and most other States of specifying the same proportions of cement and graded aggregate for concrete, regardless of the void content of these aggregates, has resulted in securing for gravel aggregate an appreciable economic advantage due to the increased yield of concrete obtained from the gravel aggregate on account of its low void content, as well as its lower cost compared with that of crushed stone. These facts, together with the other natural advantages possessed by gravel, such as the increased workability of the resulting concrete, have made its use in general more economical than crushed stone.

Such a condition would not in itself warrant any change in the existing methods of proportioning. It must be remembered, however, that the arbitrary proportions which are set are only a means to an end which, in this case, is the production of concrete possessing certain definite essential physical properties. If a specification is to be considered adequate it must be assumed that, as long as the various details of the specifications relative to materials and construction

[1]From Public Roads, Vol. 8, No. 12, Feb., 1928.

processes are complied with, concrete of substantially uniform quality will be obtained; in other words, that any variation in either type or gradation of aggregate within the specification limits will not result in any essential change in the quality of the product.

The standard road specifications of the New Jersey Highway Commission require that concrete for pavements shall be mixed in the proportions of 1 part cement to 1¾ parts sand and 3½ parts coarse aggregate by volume measured in a loose, dry condition. In the determination of the field mix, the amount of sand is proportioned on a dry, loose basis; that is, a bulking correction is made. Either crushed rock or gravel conforming to certain requirements as to quality and gradation may be used. This, as has been pointed out, results in the production of more concrete per unit volume of cement when gravel is used as coarse aggregate than when stone is used, due of course, to the higher void content of the crushed stone aggregate.

It has been repeatedly urged by the crushed-stone interests in New Jersey that concrete produced from crushed stone is of a better quality than that produced from gravel due to the difference in character of these two aggregates and to the higher cement content of the stone concrete, as expressed in terms of volume of cement required to produce a unit volume of concrete.

If these claims are true, they are of considerable significance, because it means that, if the gravel concrete produced under the present specifications is satisfactory in quality, the use of crushed stone results in the production of a higher quality of concrete than is demanded by the minimum requirements of the specifications. If, on the other hand, the crushed-stone concrete is no better than it should be, the obvious conclusion is that the gravel concrete will not meet the minimum requirements. In either event, if it is shown that the type of aggregate does affect the quality of the concrete to an appreciable degree, some readjustment should be permitted in order to insure concrete of equal quality irrespective of the type of aggregate used.

Scope of Tests and Materials Described

Recognizing the importance of this problem from both the engineering and economic points of view, the Bureau of Public Roads and the New Jersey State Highway Commission undertook a study of the question through a series of carefully controlled laboratory tests to determine the following:

1. The relative strength and yield of crushed-stone and gravel concrete of the same proportions and consistency, and with the same size and grading of coarse aggregate.

2. What grading of coarse aggregate and what proportions of fine to coarse would give the greatest yield for each type of aggregate, when the concrete is designed for a given strength.

In discussing the essential characteristics of paving concrete, it is herein assumed that in so far as strength is concerned, resistance to bending or flexure is of more significance than is resistance to crushing. Many engineers, in designing concrete pavements, employ the flexural strength of the concrete in calculations for edge and center thickness of slabs under given conditions of load and accept it as the criterion of quality rather than the compressive strength. It is obvious, therefore, that factors influencing flexural strength are of critical importance in so far as pavement concrete is concerned.

To secure flexural-strength tests that would not be unduly influenced by the size of the aggregates used, it was decided to make the major strength comparisons from the results secured with concrete beams 8 by 8 by 48 inches in size, tested as cantilevers for flexural strength using a device similar to that described by Clemmer in Public Roads for May, 1926. It was also decided to use the ends of the beams from the flexure tests as compression specimens in determining the crushing strength of the concrete as well as the 6 by 12 inch cylinders which were cast for this particular purpose. Tests were to be made on all specimens at the age of 28 days, as well as additional series of tests on the 1:1¾:3½ specimens at the age of six months. Accurate measurements of the yield of concrete obtained from each batch were also to be taken.

Thirteen gradations of crushed trap rock and gravel were employed, ranging from a 3-inch maximum down to a 1-inch maximum size. Well-graded and poorly graded combinations were used, the object being to

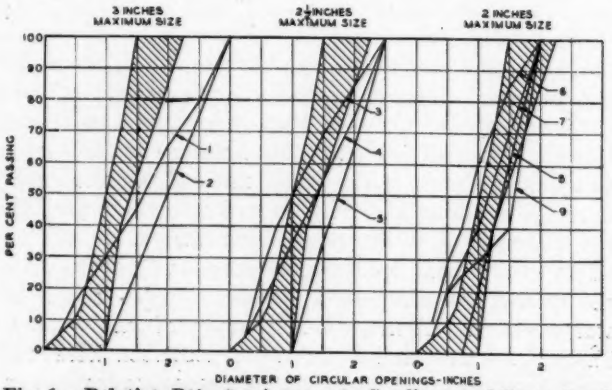

Fig. 1.—Relation Between Aggregate Gradings and State Specifications for Size of Crushed Stone. Areas Cross Hatched Indicate Specification Limits.

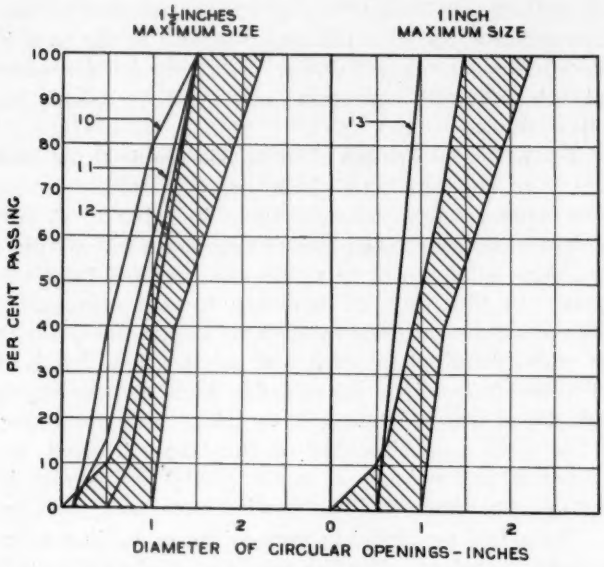

Fig. 2.—Relation Between Aggregate Gradings and State Specification for Size of Crushed Stone. Areas Cross Hatched Indicate Specification Limits.

cover quite a wide range of coarse-aggregate gradations within these limits. The exact screen analysis of each combination is shown in Table 1 and is plotted graphically in Figures 1 and 2, which also show the present New Jersey State requirements for crushed stone for concrete pavements. State requirements for gravel for concrete are similar to those for crushed stone except that more material finer than one-half inch is permitted in the gravel than the crushed stone. For convenience in visualising the gradings of the coarse aggregate, the fineness modulus of each combination was calculated and is shown in Table 2, together with the "maximum size," a value to be used in connection with any design calculations which might be made by the fineness-modulus method. This table also shows the percentage of fine aggregate required by the fineness-modulus method for each gradation calculated on the basis of the sand employed in these tests.

Table 1.—Gradings of coarse aggregates used in tests.

Coarse aggregate grading No.	Total per cent passing screens with round openings								
	3-inch	2½-inch	2-inch	1½-inch	1-inch	¾-inch	½-inch	¼-inch	⅜-inch
1	100	80	65	45	30	----	15	5	0
2	100	75	50	25	0	----	----	----	----
3	----	100	85	70	50	40	25	5	0
4	----	100	75	55	35	25	15	5	0
5	----	100	65	35	0	----	----	----	----
6	----	----	100	85	60	40	30	10	0
7	----	----	100	70	40	30	20	5	0
8	----	----	100	60	20	0	----	----	----
9	----	----	100	40	30	25	20	5	0
10	----	----	----	100	80	60	40	10	0
11	----	----	----	100	60	40	15	5	0
12	----	----	----	100	40	10	0	----	----
13	----	----	----	----	100	50	0	----	----

The crushed stone was obtained from Bound Brook, N. J., and the gravel from Morrisville, Pa. The rock is representative of the extensive deposits of basalt (trap rock) quarried in northern New Jersey. This material is very hard and tough, showing a percentage of wear of 2.2 (French coefficient equals 18.2), apparent specific gravity of 2.97 (weight per cubic foot, solid, 185 pounds), and a water absorption of 0.05 per cent. The gravel is representative of material of the type used extensively throughout this region. It consists essentially of rounded fragments of sandstone, flint, and quartz, has an apparent specific gravity of 2.65 (weight per cubic foot solid, of 165 pounds) and a water absorption of 0.68 per cent.

Table 2.—Fineness moduli of aggregates used in tests.

Coarse aggregate grading No.	Maximum size	Fineness modulus	Sand required [1]
	Inches		*Per cent*
1	3	8.0	31
2	3	8.6	39
3	3	7.5	30
4	3	7.9	30
5	3	8.4	37
6	1½	7.2	35
7	2	7.5	30
8	2	8.0	37
9	2	7.6	32
10	1	6.8	39
11	1½	7.3	37
12	1½	7.7	42
13	1	7.2	45
Sand	----	3.2	----

[1] Calculated by fineness-modulus method for a designed strength of 3,500 pounds per square inch, slump of 1 inch and with the sand employed in these tests.

The fine aggregate used in the tests was also obtained at Morrisville, Pa., and meets all the conventional tests for first-grade concrete sand. The physical properties of the sand are shown below. Its apparent specific gravity was 2.65 (weight per cubic foot, solid, 165 pounds and its weight per cubic foot, dry, and shaken to refusal 108 pounds).

Physical properties of fine aggregate consisting essentially of subangular quartz grains containing some chert and sandstone.

Sieve analysis:		
Total retained on ¼-inch screen	per cent	7
No. 10 sieve	do	24
No. 20 sieve	do	38
No. 30 sieve	do	62
No. 50 sieve	do	86
No. 100 sieve	do	95
Silt and clay	do	1.8
Weight per cubic foot (shaken to refusal)	pounds	108
Tensile strength ratio at 7 days	per cent	123
28 days	do	120

The cement was a standard Portland passing all physical test requirements. It was a brand used extensively in New Jersey.

The percentage of voids for each aggregate in each of the 13 grading combinations as calculated from the apparent specific gravities and the unit weights are shown in Table 3. These values were used in all calculations of volume-weight relations.

Table 3.—Weight per cubic foot and percentage of voids of coarse aggregates.

Coarse aggregate grading No.	Crushed stone		Gravel	
	Weight per cubic foot	Voids	Weight per cubic foot	Voids
	Pounds	*Per cent*	*Pounds*	*Per cent*
1	110	41	108	34
2	97	48	97	41
3	106	43	107	35
4	103	44	108	34
5	94	49	96	42
6	102	45	106	36
7	103	44	105	36
8	97	48	97	41
9	104	44	107	35
10	97	48	105	36
11	98	47	104	37
12	94	49	98	41
13	90	51	96	42

Test Procedure for Series A

In series A the concrete was proportioned by volume, using a nominal mix of 1:1¾:3½. As far as could be measured by the use of the flow table, a constant consistency was maintained throughout the series, the quantity of water being varied as necessary. The flow test was made on the 30-inch flow table, using 30 drops from a height of one-half inch. In this report the flow is expressed as the final diameter in tenths of inches of a truncated cone of concrete, which had an original diameter at the base of 10 inches. For example, a flow of 140 indicates a final diameter of the base of 14 inches. The consistency employed, which was as nearly as possible that required in actual construction, gave a flow of 140 corresponding to a slump of from 1 inch to 2 inches. It was found necessary to vary the water-cement ratio from 0.67 to 0.83 in order to maintain a constant consistency throughout the range of coarse-aggregate gradings. The water-cement ratios used in series A are given in Table 4. No correction for water absorbed by the aggregate was made in calculating these values.

Table 4.—Water-cement ratio used in series A to produce concrete of uniform consistency.

[Proportions: 1:1¾:3½ by volume. Consistency: Flow equals approximately 140]

Coarse aggregate grading No.	Water-cement ratio for stone concrete	Water-cement ratio for gravel concrete	Coarse aggregate grading No.	Water-cement ratio for stone concrete	Water-cement ratio for gravel concrete
1	0.76	0.76	8	0.71	0.74
2	.69	.70	9	.76	.74
3	.76	.77	10	.83	.78
4	.72	.70	11	.74	.74
5	.68	.66	12	.73	.70
6	.76	.75	13	.79	.74
7	.74	.72			

The actual quantities of materials required for each batch of concrete were determined by weight, using the volume-weight relations given in Table 3. A sufficient quantity of each size of aggregate was weighed for each batch, so as to secure the required total volume. In this way, all tendency toward segregation was avoided. In order to properly gauge the quantity of water required for each test batch, a trial batch of the same proportions was mixed by hand and the proper amount of water determined by trial. This procedure, while adding considerably to the labor involved, resulted in test batches of much greater uniformity in consistency than would otherwise have been possible.

The actual test batches were mixed in a 1-bag gasoline-driven mixer. For the gradings numbered 1 to 5, inclusive, the quantities of materials used in each batch were based on a coarse aggregate volume of 1.8 cubic feet, producing a slight excess of concrete over that required for one beam. For the gradings numbered 6 to 13, inclusive, quantities were based on a coarse-aggregate volume of 2.4 cubic feet, producing sufficient concrete for one beam and three cylinders. All batches were mixed for two minutes after all ingredients had been added. After mixing, the batch was dumped upon a water-tight platform, flow tests for consistency made, and specimens cast. Concrete was rodded into molds in accordance with approved methods of molding. Accurate determinations of yield were made by determining both the volume and the weight of the concrete remaining after the specimens had been cast.

Specimens were cured for 24 hours under damp cloths in the laboratory, after which the forms were removed and the specimens placed in a moist room until tested. Tests were made at 28 days and at 6 months.

To eliminate the effect of other variables on the relative strength of the crushed-stone and gravel concrete, specimens employing crushed stone and gravel of the same gradation were always cast in pairs. The entire series of gradations was also completed before being repeated, several days usually elapsing between the first and second rounds. Variations in temperature and humidity conditions throughout the test were compensated for in this way, making possible a more satisfactory comparison of the effect of aggregate grading on strength.

In testing the beams for flexural strength, two breaks were made on each specimen and the results averaged and reported, after calculation, as the modulus of rupture for the round. (See Table 5.) The corresponding values for round 2 were obtained in the same way. The average of the two rounds was reported as the average value for the type of aggregate, the grading, and the age involved. Each average value for modulus of rupture represents four breaks on two specimens tested on different days.

Average compression test values, as given in Table 6, were obtained in the same manner, except those for gradings Nos. 6 to 13, inclusive, each value for each round is the average of tests on three cylinders.

Test Procedure for Series B

In series B an entirely different method of proportioning was employed, but the various details of mixing, molding, curing, and testing were exactly the same as in series A. In this series the concrete was designed

Table 5.—Flexural strength of concrete specimens of series A mixed in the proportions 1:1¾:3½ by volume (nominal mix) and with a flow approximately 140.[1]

Coarse aggregate grading No.	Modulus of rupture, 28-day tests						Modulus of rupture, 6-month tests					
	Stone			Gravel			Stone			Gravel		
	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
1	545	565	555	475	530	500	610	670	640	590	585	590
2	535	515	525	470	455	460	610	590	600	575	590	580
3	620	575	600	455	510	480	630	655	640	580	560	570
4	600	630	615	520	530	525	680	650	665	605	600	600
5	540	625	580	530	555	540	675	705	690	610	590	600
6	550	555	550	455	490	470	705	770	740	625	555	590
7	505	465	485	435	480	460	680	655	670	635	555	595
8	515	515	515	435	475	455	770	660	715	655	560	610
9	550	630	590	490	605	550	700	780	740	695	675	685
10	575	610	590	540	555	550	605	735	670	595	640	620
11	690	610	650	560	490	525	670	645	660	645	550	600
12	525	585	555	520	465	490	675	685	680	580	555	570
13	555	575	565	565	535	550	690	720	705	630	580	605
Average			570			505			680			600
Maximum			650			550			740			685
Minimum			485			455			600			570

[1] Determinations made on concrete beams 8 by 8 by 48 inches in size, tested as cantilevers. Each value is the average of two breaks on one beam.

Table 6.—Compressive strength of concrete specimens of series A mixed in the proportions 1:1¾:3½ by volume (nominal mix) and with a flow of approximately 140.[1]

Coarse aggregate grading No.	Crushing strength, 28-day tests						Crushing strength, 6-month tests					
	Stone			Gravel			Stone			Gravel		
	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
1	4,255	3,160	3,710	3,580	3,020	3,300	None made.					
2	3,955	3,050	3,500	3,600	3,455	3,530						
3	4,300	3,385	3,840	3,395	3,565	3,580						
4	3,630	3,470	3,550	3,255	3,440	3,350						
5	3,510	3,760	3,635	3,475	3,370	3,420						
6	3,285	2,860	3,070	3,070	2,890	2,980	4,630	5,085	4,860	3,345	4,700	4,020
7	3,145	2,920	3,030	3,115	3,360	3,240	4,050	4,205	4,130	4,090	4,145	4,120
8	3,230	2,720	2,975	2,740	2,685	2,710	4,535	3,405	3,970	4,420	3,110	3,765
9	3,215	3,505	3,360	2,860	3,510	3,185	3,880	4,090	3,985	3,740	4,570	4,155
10	3,830	3,020	3,425	3,620	3,600	3,610	4,695	3,945	4,320	4,220	4,525	4,370
11	3,715	3,285	3,500	3,635	3,490	3,560	4,780	3,295	4,040	4,610	3,655	4,130
12	3,530	2,410	2,970	3,540	3,070	3,305	4,420	3,725	4,070	4,205	4,305	4,255
13	3,540	2,890	3,215	3,600	3,725	3,660	4,030	3,595	3,810	4,495	4,695	4,595
Average			3,370			3,340			4,150			4,180
Maximum			3,840			3,660			4,860			4,595
Minimum			2,970			2,710			3,810			3,765

[1] For coarse aggregate gradings Nos. 1 to 5, inclusive, crushing-strength tests were made on portions of beams from flexure tests; each value is the average of two tests. For coarse aggregate gradings Nos. 6 to 13, inclusive, crushing-strength tests were made on 6 by 12 inch cylinders; each value is the average of three tests.

according to the so-called trial method application of the water-cement ratio theory which is being advocated by the Portland Cement Association and which is described in a bulletin[1] published by the association. The design called for a crushing strength at 28 days of 3,500 pounds, using a water-cement ratio of 0.72. The object was to secure data showing how variations in the type and gradation of coarse aggregate and the ratio of fine to coarse aggregate would affect the strength and yield when proportioned by the trial method.

To secure a uniform consistency as used in series A but with a constant water-cement ratio, the procedure in determining the proper proportions was as follows:

A paste of water and cement in the ratio required (0.72) was prepared and added to a mixture of fine and coarse aggregate until a consistency was obtained approximating a flow of 140. Three mixtures of fine and coarse aggregate were used. They were proportioned by volume in the following ratios, 33:67, 36:64, and 40:60. Trials were made with small hand-mixed batches for each type and grading of coarse aggregate, using each of the ratios of fine to coarse aggregate, and the proportions for the test batches were calculated from the resulting weights. The calculated proportions in series B for all combinations are given in Table 7. This work was done in strict accordance with the procedure recommended by the Portland Cement Association for the design of concrete mixtures.

There were slight differences in consistency between the machine-mixed batches and the small trial batches, even when gauged with the same amount of water, and some preliminary experimental work was necessary to establish the relation between the two. After a little experience it was found possible to proportion the trial batches for a water-cement ratio of 0.72, so that the consistency of the large test batches after two minutes mixing would not vary more than ± 5 points from a flow of 140. Any batches showing a greater deviation were discarded.

The necessity of maintaining a uniform consistency was recognized. It is realized, of course, that there is an intimate relation between consistency, water-cement ratio, and proportions for different gradations of aggregate. If any two of these factors are kept constant, it is necessary to vary the other whenever the aggregate grading varies. In this case only the coarse aggregate varied and the sand remained constant. In series A the proportions and consistency were kept constant and the water-cement ratio varied, while in series B the consistency and water-cement ratio were kept constant and the proportions varied. The latter is, of course, the rational method if we assume that strength is proportional to water-cement ratio within the range of workable mixtures.

[1]Design and Control of Concrete Mixtures, published by the Portland Cement Association, Chicago, Ill.

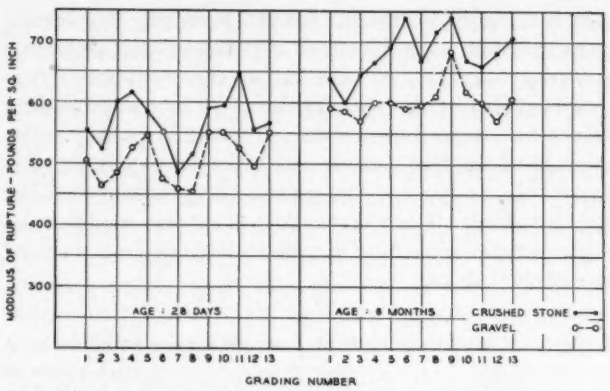

Fig. 3.—Results of Flexure Tests of Concrete Specimens of Series A.

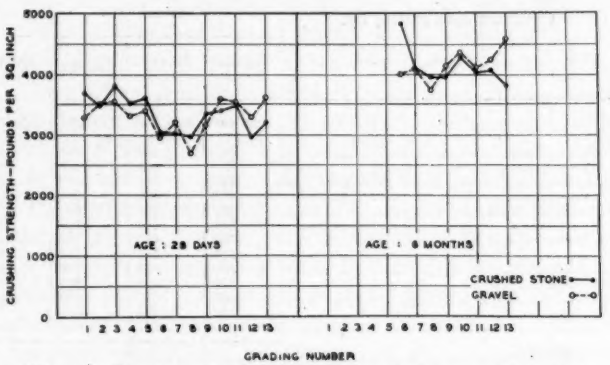

Fig. 4.—Results of Crushing Strength Tests of Concrete Specimens of Series A.

Strength Data Obtained in Series A Discussed

As previously stated, the tests included in series A were made to obtain some definite information as to the relative strength and yield of crushed-stone and gravel concrete when proportioned in accordance with current New Jersey specifications and with the various coarse-aggregate gradings indicated.

The results of the flexure tests at both 28 days and 6 months are given in Table 5 and are plotted in Figure 3. An examination of this table indicates that the crushed-stone concrete is considerably higher in flexural strength than the gravel concrete. The average increase for all 13 gradations is seen to be 65 pounds per square inch at 28 days, and 80 pounds per square inch at 6 months; approximately 13 per cent in

both cases. The concordance of the results is quite remarkable in view of the rather limited number of test specimens involved. Out of a total of 52 pairs of test specimens in the group, the crushed-stone concrete shows higher flexural strength in 49 cases; the values are the same in one case and the gravel concrete shows higher values in two cases. An inspection of the averages of the two rounds shows the crushed-stone concrete higher in all cases, as is indicated graphically in Figure 3. The results given in Table 6 and plotted in Figure 4, however, indicate that this difference is not reflected in the crushing strength of the concrete, the crushed-stone concrete in this case averaging practically the same as the gravel concrete at each period. These tables and figures do not reveal any consistent relation between either maximum size or gradation of coarse aggregate and the strength, either flexural or crushing. This is not particularly surprising in view of the small number of specimens of each gradation represented. This would seem to indicate that possibly variations in grading do not have a very marked effect upon strength, at least in so far as concrete of this particular proportion (1:1¾:3½) is concerned. It is true that a number of the mixes were undersanded when judged by the standard set-up by the fineness-modulus method of proportioning. Gradings Nos. 2, 5, 8, 10, 11, 12 and 13 when proportioned by this method would require a sand-coarse aggregate ratio of approximately 2 : 3 instead of 1 : 2 as given by the 1:1¾:3½ mix.

In the case of the smaller aggregates, as for instance gradings Nos. 10 to 13, inclusive, it is probable that this additional sand would have necessitated sufficient additional water for the same consistency to cause an appreciable lowering of the strength. Variations in the water-cement ratio required because of variations in coarse-aggregate grading with a fixed quantity of sand, as used in this series (Table 4) do not appear to be sufficient to affect the strength consistently. This fact is of considerable practical significance because it indicates that changes in the water content made necessary on the job to maintain a given consistency when variations in coarse-aggregate grading occur do not affect the strength as much as is sometimes supposed. There is, however, a very appreciable effect on yield, and therefore on relative economy, which will be discussed later.

Strength Data Obtained in Series B Discussed

The data secured as the result of tests of series B are interesting because we have not only an opportunity to study variation in strength for a fixed water-cement ratio, but we can also study the effect of variation in the ratio of sand to coarse aggregate on the strength and yield. It will be remembered that in this series the concrete was proportioned by trial so as to give a consistency of 140 by the flow test for a water-cement ratio of 0.72 and that three sand-coarse-aggregate ratios were employed, 33:67, 36:64, and 40:60. The actual proportions which were derived are given in

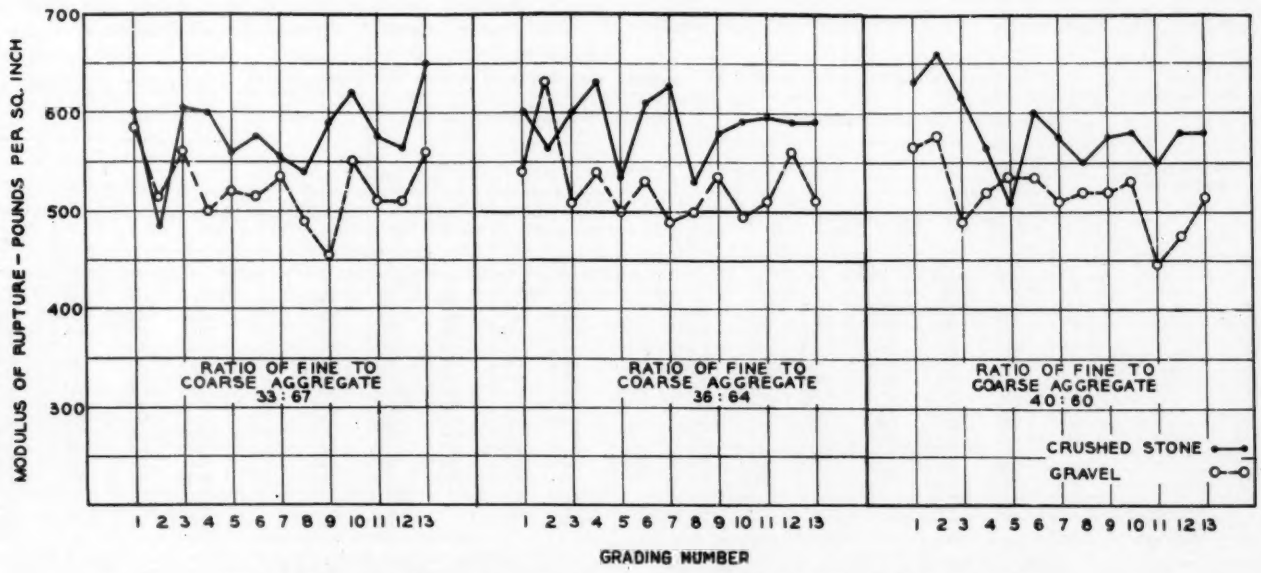
MODULUS OF RUPTURE - POUNDS PER SQ. INCH
700
600
500
400
300
RATIO OF FINE TO COARSE AGGREGATE 33 : 67
RATIO OF FINE TO COARSE AGGREGATE 36 : 64
RATIO OF FINE TO COARSE AGGREGATE 40 : 60
CRUSHED STONE
GRAVEL
1 2 3 4 5 6 7 8 9 10 11 12 13
GRADING NUMBER

Fig. 5.—Results of Flexure Tests of Concrete Specimens of Series B, 28-Day Tests

Table 7, and vary all the way from a 1:1.67:2.50 mix for grading No. 10, stone (40:60 ratio), to a 1:1.98:3.96 mix for grading No. 2, gravel (33:67 ratio). The resulting yield and therefore economy of these mixes will be discussed later. These mixes were all designed to give a crushing strength at 28 days of 3,500 pounds per square inch.

Table 7.—Proportions used in series B to obtain flow of 140 with water-cement ratio of 0.72.

Coarse aggregate grading No.	Ratio sand to coarse aggregate 33:67		Ratio sand to coarse aggregate 36:64		Ratio sand to coarse aggregate 40:60	
	Stone	Gravel	Stone	Gravel	Stone	Gravel
1	1:1.68:3.37	1:1.72:3.44	1:1.72:3.06	1:1.81:3.22	1:1.78:2.67	1:1.85:2.78
2	1:1.96:3.92	1:1.98:3.96	1:1.96:3.49	1:2.01:3.58	1:2.05:3.07	1:2.14:3.21
3	1:1.62:3.24	1:1.68:3.36	1:1.70:3.03	1:1.82:3.24	1:1.86:2.79	1:1.92:2.88
4	1:1.79:3.58	1:1.63:3.27	1:1.84:3.28	1:1.85:3.29	1:1.93:2.90	1:1.99:2.99
5	1:1.88:3.75	1:1.90:3.80	1:1.97:3.51	1:1.99:3.55	1:1.92:2.88	1:2.18:3.28
6	1:1.52:3.04	1:1.55:3.11	1:1.63:2.90	1:1.66:2.95	1:1.84:2.76	1:1.88:2.82
7	1:1.57:3.14	1:1.70:3.39	1:1.80:3.20	1:1.73:3.08	1:1.82:2.73	1:1.88:2.82
8	1:1.84:3.68	1:1.87:3.75	1:1.93:3.44	1:1.95:3.47	1:2.02:3.03	1:2.01:3.02
9	1:1.67:3.34	1:1.71:3.42	1:1.90:3.38	1:1.81:3.22	1:1.78:2.68	1:1.89:2.83
10	1:1.47:2.94	1:1.47:2.94	1:1.53:2.72	1:1.52:2.71	1:1.67:2.50	1:1.78:2.68
11	1:1.59:3.18	1:1.62:3.24	1:1.70:3.03	1:1.72:3.06	1:1.91:2.87	1:1.83:2.74
12	1:1.72:3.44	1:1.82:3.64	1:1.90:3.38	1:1.80:3.20	1:2.06:3.09	1:2.03:3.05
13	1:1.62:3.24	1:1.67:3.35	1:1.74:3.10	1:1.71:3.05	1:1.91:2.86	1:1.93:2.90

The results of the flexural strength test for each of the three aggregate ratios are shown in Table 8 and are plotted in Figure 5. Inspecting general averages, not only were almost identical values for moduli of rupture at 28 days found as were found for series A, but what is somewhat more significant, the same relative increase in strength for the crushed-stone concrete as compared with the gravel concrete was found. These average values are grouped together for comparison in Table 9 and Figure 6. The percentage of increase, is however, not quite so great, ranging from 10 per cent for the 33:67 mix to 13 per cent for the 40:60 combination.

The figures demonstrate the danger of designing concrete for resistance to flexure solely on the basis of water-cement ratio without regard to the type of aggregate employed.

Reverting again to Figure 5 and discussing the detail values for flexural strength in series B, it is seen that the graphs show considerable variation in strength. Attention should be called, however, to the fact that the vertical scale to which these values have been plotted is very large and that in reality the deviations from the group averages are in general quite small.

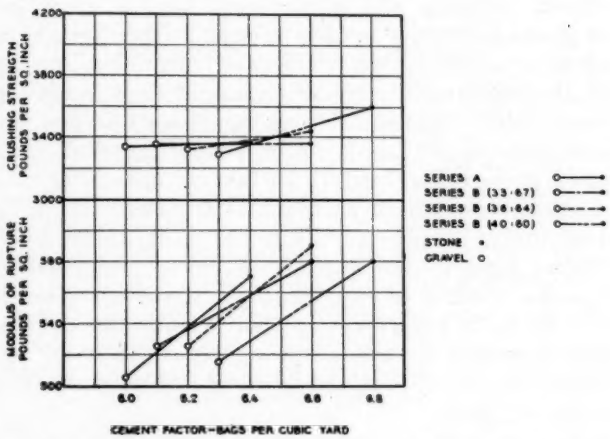

Fig. 6.—Relation Between Strength of Concrete and Cement Factor. General Averages for all Gradings.

Table 8.—Flexural strength of concrete specimens of series B, 28-day tests[1]

Coarse aggregate grading No.	Ratio sand to coarse aggregate 33:67						Ratio sand to coarse aggregate 36:64						Ratio sand to coarse aggregate 40:60					
	Stone			Gravel			Stone			Gravel			Stone			Gravel		
	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
1	660	540	600	640	530	585	615	585	600	555	555	540	690	565	630	575	550	560
2	520	450	485	515	515	515	565	560	560	570	685	630	720	595	660	625	520	570
3	570	640	605	575	540	560	560	635	600	510	505	510	585	645	615	475	505	490
4	580	620	600	505	500	500	605	655	630	525	550	540	555	570	560	525	510	520
5	590	525	560	505	530	520	560	505	530	480	525	500	495	525	510	545	520	530
6	590	565	570	530	500	515	580	640	610	500	560	530	600	605	600	530	535	530
7	565	545	555	555	510	530	665	590	630	515	465	490	565	585	575	470	550	510
8	525	550	540	490	485	490	585	475	530	525	480	500	550	545	550	490	545	520
9	575	605	590	510	400	455	600	555	580	540	525	530	575	575	575	545	490	520
10	600	645	620	505	590	550	600	580	590	510	475	490	580	575	580	540	520	530
11	595	555	575	515	500	510	600	590	595	480	535	510	575	530	550	420	465	440
12	560	570	565	515	500	510	575	600	590	545	570	560	620	535	580	490	455	470
13	665	630	650	530	585	560	595	585	590	510	510	510	595	565	580	495	535	515
Average			580			525			590			525			580			515
Maximum			650			585			630			630			660			570
Minimum			485			455			530			490			510			440

[1] Determinations made on concrete beams 8 by 8 by 48 inches in size. Each value is the average of two breaks on one beam.

Table 9.—Comparison of average results of 28-day tests of series A and series B.

Series	Coarse aggregate	Ratio of fine to coarse aggregate	Average modulus of rupture	Average crushing strength	Average cement factor
			Lbs. per sq. in.	*Lbs. per sq. in.*	*Bags per cu. yd.*
A	Stone	33:67	570	3,370	6.4
	Gravel	33:67	505	3,340	6.0
B	Stone	33:67	580	3,360	6.6
	Gravel	33:67	525	3,360	6.1
B	Stone	36:64	590	3,440	6.6
	Gravel	36:64	525	3,310	6.2
B	Stone	40:60	580	3,600	6.8
	Gravel	40:60	515	3,290	6.3

NOTE.—Each value for flexural strength is the average of 52 tests.
Each value for crushing strength is the average of 68 tests.
In series A the proportions were 1:1¼:3½ by volume; flow, 140; water-cement ratio varied from 0.67 to 0.81.
In series B the proportions were determined by trial (Portland Cement Association method to give a flow of 140, with a water-cement ratio of 0.72).

Table 10 shows the deviations in percentage of the individual values for each grading and type of aggregate from the group average. It will be seen that the average deviations for the three groups in series B are essentially the same and are slightly less than those in series A. It is interesting to note also that in six cases out of eight, grading No. 2 shows a deviation in excess of 5 per cent. This was a poorly graded material with a maximum size of 3 inches. The most significant detail as regards these figures, however, is the fact that for all intents and purposes the flexural strengths obtained in series B for each type of aggregate are practically uniform, the deviation being no more than must be expected even in carefully conducted laboratory work.

Table 10.—Deviations in per cent of individual values for flexural strength from the mean of each group and for each material, based an 28-day tests.[1]

Coarse aggregate grading No.	Series A		Series B					
			Ratio fine to coarse aggregate, 33:67		Ratio fine to coarse aggregate 36:64		Ratio fine to coarse aggregate 40:60	
	Stone	Gravel	Stone	Gravel	Stone	Gravel	Stone	Gravel
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
1	−3	−1	+3	+11	+2	+3	+9	+9
2	−8	−9	−16	−2	−5	+20	+14	+11
3	+5	−5	+4	+7	+2	−3	+6	−5
4	+8	+4	+3	−5	+7	+3	−3	+1
5	+2	+7	−3	−1	−10	−5	−12	+3
6	−4	−7	−2	−2	+3	+1	+3	+3
7	−15	−9	−4	+1	+7	−7	−1	−1
8	−10	−10	−7	−7	−10	−5	−5	+1
9	+4	+9	+2	−13	−2	+1	−1	+1
10	+4	+9	+7	+5	0	−7	0	+3
11	+14	+4	−1	−3	+1	−3	−5	−15
12	−3	−3	−3	−3	0	+7	0	−9
13	−1	+9	+12	+7	0	−3	0	0
Average deviation	6	7	5	5	4	5	5	5

[1] Total number of values, 104. Number in which deviation exceeds 10 per cent, 11; number in which deviation exceeds 5 per cent, 38; number in which deviation is 5 per cent or less, 66.

The results of crushing strength tests on specimens of series B are shown in Table 11 and are plotted in Figure 7. The group averages are summarized in Table 9. As in the case of the flexure tests, the deviation from the averages are, in general, neither consistent nor of great magnitude. Either of the three aggregate ratios seem to produce concrete of about the same strength regardless of grading, which again

Table 11.—Results of crushing strength tests of specimens of series B at age of 28 days[1]

RATIO OF FINE TO COARSE AGGREGATE 33 : 67

Coarse aggregate grading No.	Crushed stone			Gravel		
	Round No. 1	Round No. 2	Average	Round No. 1	Round No. 2	Average
	Lbs. per sq. in.	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*
1	3,370	3,215	3,290	3,230	3,595	3,410
2	3,370	3,040	3,205	3,220	3,185	3,200
3	4,230	3,860	4,045	3,785	3,855	3,820
4	3,825	4,065	3,945	3,690	3,240	3,465
5	3,590	3,150	3,370	3,820	2,605	3,210
6	3,710	3,205	3,460	3,345	4,075	3,710
7	3,455	3,145	3,300	3,375	3,410	3,390
8	2,950	2,645	2,800	3,200	3,210	3,205
9	3,695	2,985	3,340	3,365	3,720	3,540
10	4,025	3,090	3,560	3,490	3,405	3,450
11	3,710	3,000	3,355	3,635	2,880	3,210
12	3,025	2,580	2,800	3,120	2,535	2,830
13	3,465	2,945	3,205	3,205	3,315	3,260
Average			3,360			3,360
Maximum			4,045			3,820
Minimum			2,800			2,830

RATIO OF FINE TO COARSE AGGREGATE 36 : 64

1	3,520	3,245	3,380	3,605	3,385	3,495
2	3,090	3,075	3,080	3,245	4,015	3,630
3	3,975	3,560	3,770	3,165	3,160	3,160
4	3,645	4,060	3,850	3,190	3,325	3,260
5	3,455	3,375	3,415	2,975	3,685	3,330
6	3,790	3,805	3,800	3,190	3,815	3,500
7	3,285	3,925	3,605	3,085	3,215	3,150
8	2,845	2,895	2,870	2,885	2,725	2,805
9	3,125	3,190	3,160	3,170	3,000	3,085
10	3,550	3,950	3,750	3,640	3,680	3,660
11	3,175	3,785	3,480	3,225	3,935	3,580
12	3,025	3,310	3,170	3,440	2,990	3,215
13	3,225	3,580	3,400	2,870	3,515	3,190
Average			3,440			3,310
Maximum			3,850			3,660
Minimum			2,870			2,805

RATIO OF FINE TO COARSE AGGREGATE 40 : 60

1	3,970	3,360	3,665	3,040	3,460	3,250
2	3,335	3,805	3,570	3,490	3,425	3,460
3	3,765	4,065	3,915	3,045	3,890	3,470
4	3,670	4,190	3,930	3,240	2,895	3,070
5	3,500	3,590	3,545	3,365	3,150	3,260
6	4,165	3,385	3,775	3,490	3,460	3,475
7	3,540	2,865	3,200	3,180	3,630	3,405
8	3,200	3,060	3,130	3,285	3,115	3,200
9	3,720	3,475	3,600	3,190	2,970	3,080
10	4,055	3,920	3,990	3,610	3,260	3,435
11	3,610	3,600	3,605	3,480	3,285	3,380
12	3,145	3,235	3,190	3,020	2,625	2,820
13	3,435	3,905	3,670	3,540	3,365	3,450
Average			3,600			3,290
Maximum			3,990			3,475
Minimum			3,130			2,820

[1] For coarse-aggregate gradings 1 to 5, inclusive, crushing-strength tests were made on portion of beams from flexure tests. Each value is the average of two breaks. For coarse-aggregate gradings 6 to 13, inclusive, crushing-strength tests were made on 6 by 12 inch cylinders. Each value is average of three tests.

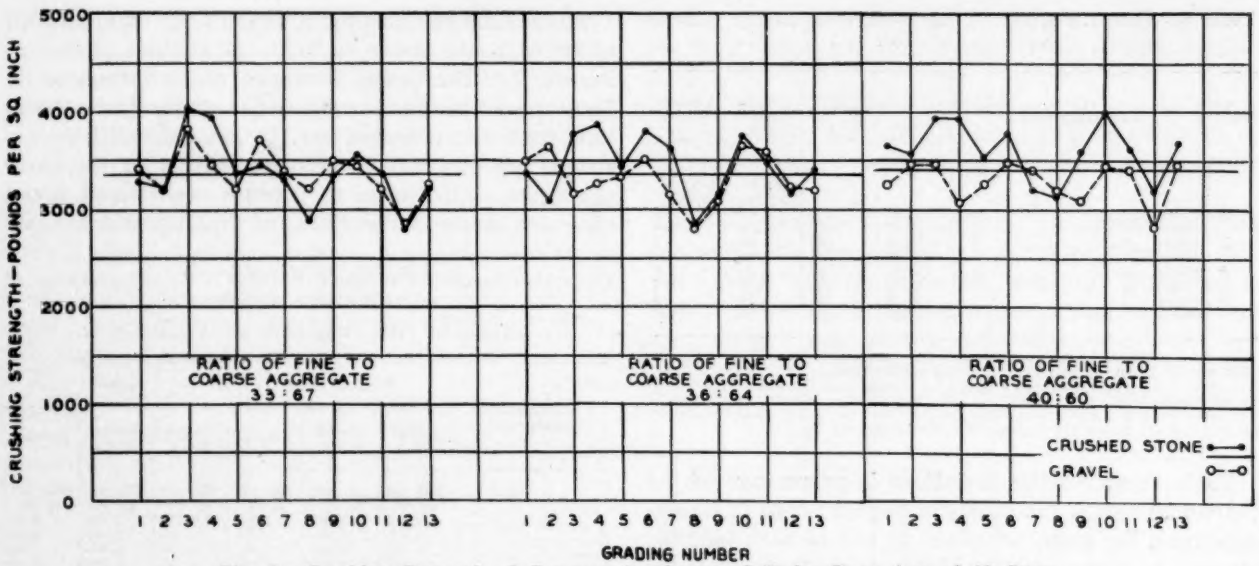

Fig. 7.—Crushing Strength of Concrete Specimens of Series B at Age of 28 Days

seems to indicate that so far as strength alone is concerned grading of coarse aggregate within the limits here indicated is not an important factor. The words "strength alone" are used here and elsewhere advisedly.

Aside from the yield or relative economy of the different gradations, which is a subject entirely apart from the question of quality, variations in grading which produce harsh concrete difficult to handle and place, will unquestionably affect the strength on the job, because of the invariable tendency of the concrete gang to use excess water with such a mix. In these tests an effort was made to secure comparable workability of the different batches by means of the flow test. The slump test was, of course, entirely unsuited to this kind of work. The flow test was used because there was nothing better. It is, however, not a test for workability in the strict sense of the word, so that several of the undersanded mixtures with the ratio of fine to coarse aggregate of 33:67 were probably unworkable in the sense that they would have been difficult to place and finish on the job. The point that it is intended to emphasize is, that it was possible to control the water-cement ratio in the laboratory but it would not be at all easy in actual construction unless the control was very rigid.

Absorption Tests Made

A short series of absorption tests was made on the concrete of series A at age of six months. The results are given in Table 12 and indicate that there is practically no difference between the absorption of the stone and the gravel concrete. These tests were made by immersing samples of concrete from the broken beams in water for 24 hours and noting the increase in weight.

Table 12.—Absorption tests on concrete of series A at age of six months

Coarse aggregate grading No.	Water absorbed by stone concrete			Water absorbed by gravel concrete		
	Specimen No. 1	Specimen No. 2	Average	Specimen No. 1	Specimen No. 2	Average
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	5.5	5.0	5.3	4.8	5.9	5.4
2	5.8	4.8	5.3	4.8	5.2	5.0
3	5.9	5.6	5.8	5.6	5.5	5.6
4	4.3	5.1	4.7	4.5	5.0	4.8
5	4.3	5.6	5.0	4.9	5.0	5.0
6	5.6	5.6	5.6	5.6	5.8	5.7
7	5.6	5.6	5.6	5.1	4.9	5.0
8	5.0	6.3	5.7	5.0	5.4	5.2
9	6.0	5.8	5.9	4.8	5.2	5.0
10	6.2	5.8	6.0	5.1	6.0	5.6
11	5.2	5.7	5.5	4.8	5.9	5.4
12	4.9	5.0	5.0	5.2	5.8	5.5
13	5.4	5.8	5.6	5.6	5.5	5.6
Average			5.5			5.3

Yield of Concrete Discussed

A study of the relative economy of various concrete mixtures, all of which may have the same strength, is just beginning to occupy the attention of engineers and progressive contractors. It was formerly assumed and is still stated in many handbooks that, for a given proportion of cement, sand, and coarse aggregate, definite amounts of materials are required to produce a

cubic yard of concrete. While the values given may be correct as average values it is known that there are many factors which may appreciably alter any one or more of these quantities under certain conditions. In this report the writer is concerned primarily with the effect of type and gradation of coarse aggregate on yield.

Series A

Table 13 gives the computed quantities of material required for 1 cubic yard of concrete for each type and gradation of aggregate used in these tests, while Table 14 gives the corresponding solid volumes of the materials and the density of the concrete (total solids expressed as a percentage of 27 cubic feet). Quantities of materials are plotted in Figures 8 and 9. These figures illustrate graphically the fluctuations in the quantities of materials required to produce 1 cubic yard of concrete due to variations in the grading of the coarse aggregate. Assuming unit costs for cement, sand, and coarse aggregate, these values may be used to determine the cost of the materials in a cubic yard of concrete for each grading and aggregate type shown. Allowance should be made for the fact that the figures for any particular case may be somewhat out of line because of inaccuracies which result from experimental errors. For this reason, comparisons of the effect of aggregate type on yield should only be made on averages for all gradations, as in this way the number of specimens tend to largely eliminate the effect of experimental errors. The results for the individual gradings, however, are of interest to the extent that they indi-

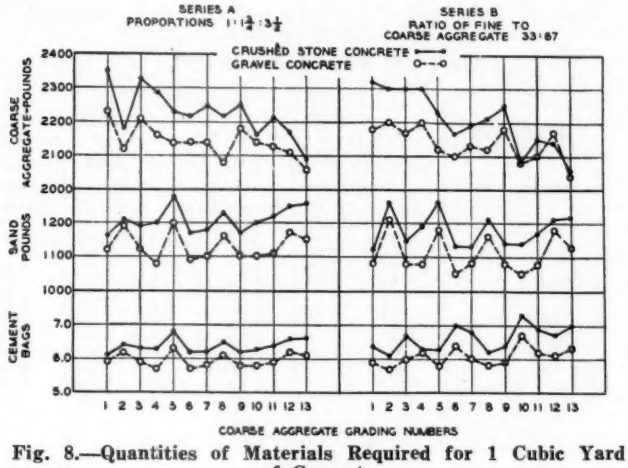

Fig. 8.—Quantities of Materials Required for 1 Cubic Yard of Concrete

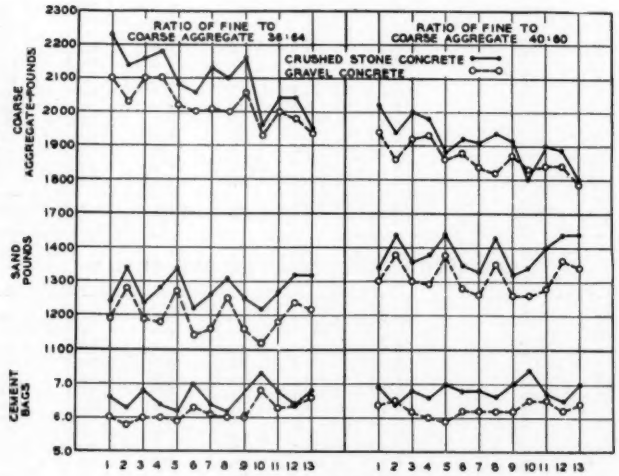

Fig. 9.—Quantities of Materials Required for 1 Cubic Yard of Concrete

Table 13.—Quantities of material required for 1 cubic yard of concrete, using the proportions 1:1¾:3½ by volume (nominal mix, series A).

Coarse aggregate grading No.	Stone			Gravel		
	Cement	Sand	Stone	Cement	Sand	Gravel
	Bags	*Pounds*	*Pounds*	*Bags*	*Pounds*	*Pounds*
1	6.1	1,160	2,350	5.9	1,120	2,230
2	6.4	1,210	2,180	6.2	1,190	2,120
3	6.3	1,190	2,330	5.9	1,120	2,210
4	6.3	1,200	2,290	5.7	1,080	2,160
5	6.8	1,280	2,230	6.3	1,200	2,140
6	6.2	1,170	2,220	5.7	1,090	2,140
7	6.2	1,180	2,250	5.8	1,100	2,140
8	6.5	1,230	2,220	6.1	1,160	2,080
9	6.2	1,170	2,250	5.8	1,100	2,180
10	6.3	1,200	2,160	5.8	1,100	2,140
11	6.4	1,220	2,210	5.9	1,110	2,130
12	6.6	1,250	2,170	6.2	1,170	2,110
13	6.6	1,260	2,090	6.1	1,150	2,060
Average	6.4	1,210	2,230	6.0	1,130	2,140

Table 14.—Solid volumes of material for 1 cubic yard of concrete for each mix of series A and total solids or density of concrete expressed as a percentage of maximum possible density.

Coarse aggregate grading No.	Stone				Gravel			
	Solid volumes			Total solids	Solid volumes			Total solids
	Cement	Sand	Stone		Cement	Sand	Gravel	
	Cu. ft.	*Cu. ft.*	*Cu. ft.*	*Per cent*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Per cent*
1	2.96	7.04	12.70	84	2.86	6.79	13.52	86
2	3.11	7.33	11.78	81	3.01	7.21	12.84	85
3	3.06	7.22	12.60	85	2.86	6.79	13.40	85
4	3.06	7.27	12.38	84	2.77	6.54	13.10	83
5	3.30	7.76	12.05	86	3.06	7.27	12.98	86
6	3.01	7.09	12.00	82	2.77	6.61	12.98	83
7	3.01	7.15	12.17	83	2.82	6.67	12.98	83
8	3.16	7.45	12.00	84	2.96	7.03	12.60	84
9	3.01	7.09	12.17	83	2.82	6.67	13.21	84
10	3.06	7.27	11.68	81	2.82	6.67	12.98	83
11	3.11	7.39	11.94	83	2.86	6.73	12.91	83
12	3.21	7.58	11.72	83	3.01	7.09	12.79	85
13	3.21	7.64	11.30	82	2.96	6.97	12.49	83

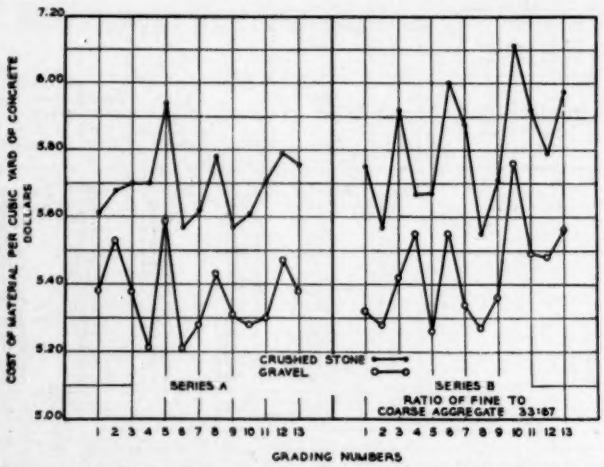

Fig. 10.—Relation Between Grading of Coarse Aggregate and Total Cost of Material to Produce 1 Cubic Yard of Concrete.

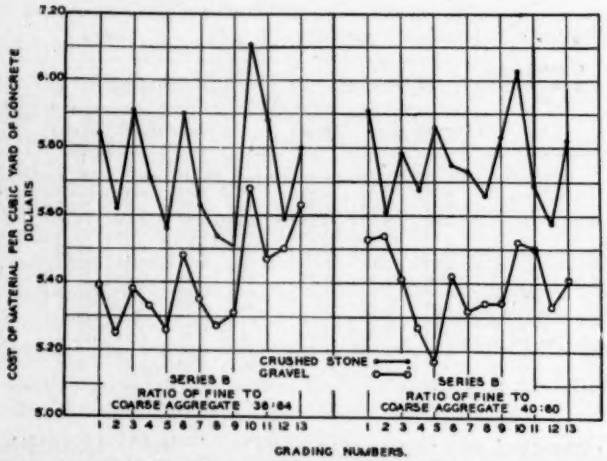

Fig. 11.—Relation Between Grading of Coarse Aggregate and Total Cost of Material to Produce 1 Cubic Yard of Concrete.

cate general relationships. For example, Figures 8 and 9 show at a glance the effect of gradings 2, 5, 8, 12, and 13 on the various quantities required to produce a cubic yard of concrete. The amount of cement and sand required is larger and the amount of coarse aggregate required is smaller than where the coarse aggregate contains the smaller sizes.

To bring out certain possible cost relations and illustrate the economic features involved in this study in a more graphic way than could be done by a comparison of quantities only, certain unit costs of materials have been assumed. These costs are said to apply fairly well to conditions in New Jersey and are as follows: Cement, 60 cents per bag; sand, 50 cents per ton; and coarse aggregate $1.40 per ton. The resulting material costs per cubic yard are shown in Figures 10 and 11. Note the relative high cost resulting from the use of gradings 2, 5, 8, and 12 of series A. The value for grading No. 2 crushed stone is evidently in error as this point should be considerably higher than shown. On the basis of the above unit prices, the average cost of materials for 1 cubic yard of gravel concrete 1:1¾:3½ mix by volume is $5.38, while the corresponding value for the crushed stone concrete is $5.70, an increase of 32 cents, or approximately 6 per cent. These values and those for series B, together with the corresponding moduli of rupture are given in Table 17. Values may be calculated in a similar way for any combination of unit prices.

Table 15.—Quantities of materials required for 1 cubic yard of concrete, series B.

RATIO OF FINE TO COARSE AGGREGATE 33 : 67

Coarse aggregate grading No.	Stone			Gravel		
	Cement	Sand	Stone	Cement	Sand	Gravel
	Bags	*Pounds*	*Pounds*	*Bags*	*Pounds*	*Pounds*
1	6.4	1,120	2,320	5.9	1,080	2,180
2	6.1	1,260	2,300	5.7	1,210	2,200
3	6.7	1,150	2,300	6.0	1,080	2,170
4	6.3	1,190	2,300	6.2	1,080	2,200
5	6.3	1,280	2,230	5.8	1,170	2,120
6	7.0	1,130	2,170	6.4	1,050	2,100
7	6.8	1,130	2,190	6.0	1,080	2,130
8	6.2	1,210	2,210	5.8	1,160	2,120
9	6.4	1,140	2,250	5.9	1,080	2,180
10	7.3	1,140	2,080	6.7	1,050	2,080
11	6.9	1,170	2,150	6.2	1,080	2,100
12	6.7	1,210	2,140	6.1	1,190	2,170
13	7.0	1,220	2,060	6.3	1,130	2,040
Average	6.6	1,180	2,210	6.1	1,110	2,140

RATIO OF FINE TO COARSE AGGREGATE 36 : 64

1	6.6	1,240	2,230	6.0	1,190	2,100
2	6.3	1,340	2,140	5.8	1,280	2,030
3	6.8	1,240	2,160	6.0	1,190	2,100
4	6.4	1,280	2,180	6.0	1,180	2,100
5	6.2	1,340	2,080	5.9	1,270	2,020
6	7.0	1,220	2,060	6.3	1,140	2,000
7	6.4	1,260	2,130	6.1	1,160	2,010
8	6.2	1,310	2,100	6.0	1,250	2,000
9	6.1	1,250	2,160	6.0	1,160	2,060
10	7.4	1,220	1,960	6.8	1,120	1,930
11	6.8	1,270	2,040	6.3	1,180	2,000
12	6.4	1,320	2,040	6.4	1,240	1,980
13	6.8	1,320	1,950	6.6	1,220	1,940
Average	6.6	1,280	2,100	6.2	1,200	2,020

RATIO OF FINE TO COARSE AGGREGATE 40 : 60

1	6.9	1,340	2,020	6.4	1,300	1,940
2	6.4	1,440	1,940	6.5	1,380	1,860
3	6.8	1,360	2,000	6.2	1,300	1,920
4	6.6	1,380	1,980	6.0	1,290	1,930
5	7.0	1,440	1,880	5.9	1,380	1,860
6	6.8	1,350	1,920	6.2	1,280	1,880
7	6.8	1,330	1,910	6.2	1,260	1,840
8	6.6	1,430	1,940	6.2	1,350	1,820
9	7.0	1,320	1,920	6.2	1,260	1,870
10	7.4	1,340	1,800	6.5	1,260	1,830
11	6.7	1,400	1,900	6.5	1,280	1,840
12	6.5	1,440	1,890	6.2	1,360	1,840
13	7.0	1,440	1,800	6.4	1,340	1,790
Average	6.8	1,390	1,920	6.3	1,310	1,860

Yield of Series B

Data for quantities of material used and densities of concrete as determined for series B are shown in Tables 15 and 16. The quantities and corresponding costs are plotted in Figures 8, 9, 10, and 11 and Table 17. These data show approximately the same relative difference in cost between the gravel and the stone concrete as in series A. It is interesting to note, however, that one factor which produces high costs in concrete proportioned as in series A, has just the opposite effect when proportioning is by the water-cement ratio trial method. When a contractor is working under a straight water-cement ratio specification, and sand is cheaper than coarse aggregate, as in this case, it is to his advantage to use a poorly graded stone or gravel because in so doing he is able to crowd more aggregate into his cement paste before passing the bounds of workability. On the other hand, the high cost of using a grading such as No. 10 with a large proportion of relatively small sizes is at once apparent, especially with the smaller proportions of sand.

Table 16.—Solid volumes of material for 1 cubic yard of concrete for each mix of series B and total solids or density of concrete expressed as a percentage of maximum possible density.

RATIO OF FINE TO COARSE AGGREGATE 33 : 67

Coarse aggregate grading No.	Stone				Gravel			
	Solid volumes			Total solids	Solid volumes			Total solids
	Cement	Sand	Stone		Cement	Sand	Gravel	
	Cu. ft.	*Cu. ft.*	*Cu. ft.*	*Per ct.*	*Cu. ft.*	*Cu. ft.*	*Cu. ft.*	*Per ct.*
1	3.11	6.79	12.54	83	2.86	6.54	13.21	84
2	2.97	7.64	12.42	85	2.77	7.34	13.34	87
3	3.26	6.97	12.42	84	2.91	6.54	13.15	84
4	3.08	7.22	12.42	84	3.01	6.54	13.34	85
5	3.06	7.64	12.05	84	2.81	7.10	12.85	84
6	3.40	6.85	11.74	82	3.11	6.36	12.71	83
7	3.30	6.85	11.84	81	2.91	6.54	12.91	84
8	3.01	7.33	11.95	83	2.81	7.03	12.85	84
9	3.11	6.97	12.16	82	2.86	6.54	13.20	84
10	3.54	6.91	11.25	80	3.25	6.36	12.60	82
11	3.35	7.09	11.62	82	3.01	6.54	12.71	82
12	3.25	7.34	11.56	82	2.96	7.15	13.16	86
13	3.40	7.40	11.13	81	3.05	6.84	12.36	82
RATIO OF FINE TO COARSE AGGREGATE 36 : 64								
1	3.21	7.52	12.06	84	2.91	7.22	12.73	85
2	3.06	8.12	11.57	84	2.82	7.76	12.30	85
3	3.30	7.52	11.67	83	2.91	7.22	12.73	85
4	3.11	7.76	11.79	84	2.91	7.16	12.73	85
5	3.01	8.12	11.24	83	2.86	7.70	12.24	84
6	3.40	7.40	11.14	81	3.06	6.91	12.12	82
7	3.11	7.64	11.51	82	2.96	7.03	12.18	82
8	3.01	7.94	11.36	83	2.91	7.58	12.12	84
9	2.96	7.58	11.68	82	2.91	6.91	12.48	83
10	3.60	7.40	10.60	80	3.30	6.79	11.70	81
11	3.30	7.70	11.03	82	3.01	7.15	12.12	83
12	3.11	8.00	11.03	82	3.11	7.52	12.00	84
13	3.30	8.00	10.54	81	3.21	7.39	11.75	83
RATIO OF FINE TO COARSE AGGREGATE 40 : 60								
1	3.35	8.12	10.91	83	3.11	7.88	11.75	84
2	3.11	8.73	10.49	83	3.16	8.36	11.27	84
3	3.30	8.24	10.81	83	3.01	7.88	11.64	83
4	3.20	8.36	10.70	82	2.91	7.82	11.69	83
5	3.40	8.73	10.16	83	2.86	8.36	11.27	83
6	3.30	8.18	10.38	81	3.01	7.76	11.39	82
7	3.30	8.06	10.32	80	3.01	7.64	11.15	81
8	3.20	8.67	10.49	83	3.01	8.18	11.03	82
9	3.40	8.00	10.38	81	3.01	7.64	11.33	81
10	3.59	8.12	9.73	79	3.16	7.64	11.09	81
11	3.26	8.49	10.27	82	3.16	7.76	11.15	82
12	3.16	8.73	10.21	82	3.01	8.24	11.15	83
13	3.40	8.73	9.73	81	3.11	8.12	10.85	82

Table 17.—Average costs per cubic yard of concrete, series A and B.

Series	Coarse aggregate	Ratio of fine to coarse aggregate	Cost of concrete per cubic yard	Average modulus of rupture 28 days
A	Stone	33:67	$5.70	570
	Gravel	33:67	5.38	505
B	Stone	33:67	5.80	580
	Gravel	33:67	5.45	525
	Stone	36:64	5.75	590
	Gravel	36:64	5.40	525
	Stone	40:60	5.75	580
	Gravel	40:60	5.40	515

Costs based on the following assumed unit prices: Cement, $0.60 per bag; sand, $0.50 per ton; coarse aggregate, $1.40 per ton.

Slabs of Equivalent Strength Determined

It is of interest to compute the relative theoretical thicknesses of slab required to produce pavements of equivalent transverse strength, using the average values of modulus of rupture for the two classes of concrete as shown by the tests of series A. For this purpose the so-called corner formula,[2] which is used extensively in the calculation of edge thickness for concrete pavement slabs, is employed. This formula is usually expressed as follows:

$$d = \sqrt{\frac{3P}{s}}$$

in which d=depth of slab in inches;
s=allowable unit flexural stress in bending in the concrete;
and P=allowed wheel-load at corner in pounds.

In both cases the usual maximum allowable unit stress of one-half the modulus of rupture will be employed in the calculation. In the case of the gravel concrete this gives an allowable stress of 253 pounds per square inch and for the stone concrete a corresponding value of 285 pounds per square inch. Assuming a load at the corner of 8,000 pounds in each case, the value of d for the crushed-stone concrete reduces to 9.18 inches and for the gravel concrete to 9.74 inches, an increase of 0.56 inch, or 6.1 per cent. For equivalent slab strengths and on the basis of the flexural-strength values in the concrete obtained from these tests, pavements constructed of gravel concrete should be approximately one-half inch thicker than pavements constructed of crushed-stone concrete.

[2] Older, Clifford. Highway Research in Illinois. Proc. A. S. C. E., 1924, p. 1180.

Reverting again to the previously assumed unit costs and adding 6.1 per cent to the cost of 1 cubic yard of gravel concrete as shown at $5.38, a value of $5.71 is obtained, which is almost exactly equal to the unit cost per cubic yard of the stone concrete. In other words, for the unit prices assumed, the cost of materials required to produce concrete pavements of the same slab strength is almost exactly the same for both aggregates. A similar cost analysis may, of course, be made with any other combination of unit prices. For example, assuming cement at 50 cents per bag, sand and gravel at $1.20 per ton, and crushed stone at $1.40 per ton, the unit cost of a cubic yard of gravel concrete (series A) is found to be $4.96, with $5.49 as the corresponding cost for the stone concrete, an increase of 53 cents. In this case, adding 6½ per cent to the cost of the gravel concrete to care for the added thickness, makes the total cost of material in a gravel concrete slab of equivalent strength $5.26 as against $5.49 for the stone concrete.

These figures are given solely to illustrate how fluctuations in material prices affect relative costs and not with any idea that they may be applied to any specific conditions. It should also be noted that, theoretically, there will be a somewhat higher labor cost in placing the gravel due to its extra thickness, although this item might possibly be somewhat neutralized by the greater workability of the gravel concrete as compared with the crushed-stone concrete.

Conclusions Presented

It is not intended that the conclusions given below and which are based on the results of these tests shall be considered as applicable to crushed trap rock and gravel of a different type and quality than those employed in this investigation, or to kindred aggregates produced and marketed under conditions differing from those used, and should not be interpreted as applying to crushed-stone or gravel aggregates in general. These conclusions are as follows:

1. That when coarse aggregates comparable in quality to those used in these tests are employed in the construction of concrete pavements in New Jersey under existing specifications:

(a) Concrete in which crushed trap rock is used as coarse aggregate will average about 12 per cent higher in flexural strength than concrete in which gravel is used as coarse aggregate.

(b) There will be practically no difference in the crushing strength of crushed trap-rock concrete and gravel concrete.

(c) There will be practically no difference in the absorption of crushed trap-rock concrete and gravel concrete.

(d) For equivalent flexural slab strengths, a pavement constructed of gravel concrete should have a depth approximately one-half inch greater than a pavement constructed of crushed trap-rock concrete.

(e) The cost of the materials required for a unit volume of crushed trap-rock concrete will as a rule be greater than the cost of materials required for an equivalent volume of gravel concrete.

2. That when coarse aggregates comparable to those used in these tests are used in concrete mixtures designed for a given strength by the so-called water-cement ratio trial method:

(a) The flexural strength of the crushed trap-rock concrete will average about 11 per cent higher than the gravel concrete.

(b) There will be practically no difference in the crushing strength of the crushed trap-rock concrete and the gravel concrete.

In addition to the above, the following indications as to effect of gradation on strength and yield when the concrete is proportioned by fixed volume as well as by the water-cement ratio theory may be stated:

(1) That the gradation of the coarse aggregate has very little direct effect upon the strength of the concrete.

(2) That when proportioned by the water-cement ratio trial method, variations in the fine-coarse aggregate ratio of from 1:2 to 2:3 do not affect the strength of the concrete for a given sand and for a given water-cement ratio.

(3) That variation in coarse aggregate grading will greatly affect the yield of concrete and therefore its cost, when the concrete is proportioned either in the usual way or by the water-cement ratio method.

(4) That the use of well-graded coarse aggregate will increase the yield when proportioned by the usual method, but exactly the reverse is the case when the concrete is proportioned by the water-cement ratio method.

Discussion of The Bureau of Public Roads—New Jersey Tests

By A. T. Goldbeck, *Director,*
Bureau of Engineering, The National Crushed Stone Association

THE TESTS described on the preceding pages are of very great significance, primarily because they show the influence which the coarse aggregate may have on the kind of strength which is so desirable for concrete road construction, namely, transverse strength. It is a fact that high compressive strength may be obtained even with the use of comparatively inferior coarse aggregates, but apparently the transverse strength of concrete is influenced by the characteristics of the coarse aggregates. For those who are not informed on the importance of high resistance to cross-bending or to direct tension in concrete for highway construction, it will not be amiss to enter into a brief discussion of this matter.

The Forces Which Concrete Roads Must Resist

Concrete is not the extremely rigid material which its appearance indicates. It can be bent, stretched or compressed, and just as long as it is not subjected to excessive stretching, bending or compression, apparently it remains in its original condition, free from tension cracks or other signs of failure. On the other hand, too much stretching of the concrete, whether by direct forces or by the bending of the slab under traffic will produce a tension failure as evidenced by cracking. If too high a compressive force is created the usual external evidence is shattering of the concrete. Failure by shear is still another form of failure of concrete which, in general, does not seem to be particularly important in concrete roads. In order to understand the relative importance of tension, cross-bending resistance and compressive resistance of concrete, let us give some thought to the forces to which a concrete road slab is subjected.

Soon after concrete is laid and has hardened it is cured under moist conditions. Since moisture keeps it swollen or expanded, it is placed under slight compression and would remain so as long as it is wet were

HIGH POINTS IN THE DISCUSSION

1. Due to bending, the compressive stress produced is only 1/5 to 1/7 of the compressive strength of the concrete when the tensile stress produced simultaneously is sufficient to cause a crack to form.

2. Direct tension and tension produced by bending are highly important stresses and determine the resistance to cracking of a concrete road.

3. The compressive stresses in concrete roads of proper design are negligible because they rarely approach the compressive strength of the concrete.

4. Small differences in modulus of rupture of concrete may make for large differences in the amount of cracking of a concrete road because the design stress almost equals the stress which produces failure under repeated loads.

5. Trap rock and dolomite both gave higher values for modulus of rupture than gravel of high quality even with a lower cement content per cubic yard, and much higher than soft, friable gravel in the Bound Brook Tests, as follows:

Coarse Aggregate	Modulus of Rupture	Cement Per Cu. Yd.
Trap and dolomite	683	6.1
High quality gravel	629	6.21
Soft, friable gravel	552	6.4

6. The Bound Brook Tests show that the stone concrete requires less cement than the gravel concrete for equal slab strength, and the proper relation for these particular materials is approximately as follows:

Coarse Aggregate	Probable Ratio of Cement for Equal Modulus of Rupture
Crushed stone	6.0 bags per cu. yd.
High quality gravel	6.6 bags per cu. yd.
Soft, friable gravel	7.8 bags per cu. yd.

7. In the Bureau of Public Roads Tests it is conclusively shown that the 1:1¾:3½ trap rock concrete averaged 13 per cent higher in cross-bending resistance or modulus of rupture than the gravel concrete of similar proportions, thus requiring 6½ per cent or approximately ½ inch extra slab thickness in the gravel slab.

8. The Minnesota Tests indicate that the round, smooth gravel does not give as high cross-breaking resistance as crushed trap or crushed limestone or gravel containing crushed fragments.

The ratio is:

Coarse Aggregate	Charted Values of Modulus of Rupture	Per Cent
Trap rock	890	122.0
Limestone	830	113.7
Smooth gravel	730	100
Gravel containing crushed fragments	810	111

9. That angularity and roughness of surface increase the modulus of rupture is indicated in the Minnesota Tests by the following comparison:

Coarse Aggregate	Modulus of Rupture from Chart
Smooth rounded gravel	730
Same gravel containing crushed oversize	810

10. That the quality of the stone or gravel influences the cross-breaking strength is shown by the fact that in the Minnesota Tests soft sandstone with 11.1 per cent wear had only 670 pounds per square inch modulus of rupture compared with the above values. In the Bound Brook Tests the soft gravel tested only 552 as compared with 629 pounds per square inch, modulus of rupture shown by the high quality gravel.

11. A change in concrete proportions or a change in road design should be made to bring about equal resistance to bending.

it not for variations in temperature. At night the temperature generally falls and contraction of the concrete results and tension may be produced of high enough value to crack the slab transversely, perhaps one day after the concrete is laid. When the curing period has ended the concrete dries out, and since moisture has somewhat the same effect on concrete as on timber, it shrinks and in so doing draws itself over the subgrade. As the slab can not readily slide, its motion is resisted by forces of friction and tension is set up, tending to crack the slab transversely. It is thus evident that it is desirable to have high resistance to tension in the early stages of hardening of concrete used for concrete surfaces. Should expansion take place due to a rise in temperature, compressive stress will be created, but this stress can not be great during the period when the concrete is shrinking and is not important in the early stages of hardening nor even in the later stages if the road is properly designed.

When the road is opened to traffic the heavy wheel loads cause bending of the slab. If the wheel is placed at a corner formed by a transverse joint and the side of the slab, that corner is bent down and, as a result of the bending, tension is produced in the top of the slab and compression in the bottom. These tensile and compressive stresses are practically of identical amounts as shown by actual measurement. This stress condition is shown in Figure 1-A.

When the wheel load is placed at the edge of the slab at some distance from a corner, the slab is bent as shown in Figure 1-B. In this case horizontal compressive stress is created at the top of the slab and horizontal tension at the bottom. Again, the tension is equal to the compression and this is a very important fact in demonstration of the great significance of the transverse test for concrete for use in highways.

Ordinarily, road concrete has a compressive resistance of 3500 pounds per square inch, but it has a tensile resistance in bending of perhaps only 1/5 to 1/7 of this amount. It follows, then, that since the bending creates horizontal compressive and tensile stresses of like amount, distributed as shown in Figures 1-A and 1-B, failure in bending is due to a failure of the concrete on the tension side and not on the compression side. Concrete is amply strong in compression but is very weak in tension.

The compressive stresses to which concrete in concrete roads may be subjected are produced, first, by the actual vertical pressure under wheel loads; second, by the compressive stresses due to bending; and, third, by horizontal expansion of the slab due to moisture and temperature. The vertical compressive stress due to wheel loads can be dismissed immediately for it is always of negligible amount. That this statement is true is shown by the fact that truck wheel-load pressures seldom exceed 800 pounds per inch of width of tire and the length of support due to flattening of the tire is often 12 to 15 inches. Horizontal compressive stresses due to bending, as has just been pointed out, may be ignored because a bending failure is a failure due to the weakness of concrete in tension and not in compression. Under the action of expansion forces it is possible to produce high compressive stresses, the effect of which is to buckle the slab and cause it to rise from the subgrade, sometimes accompanied by shattering of the concrete. The slab acts much like a long column and buckling is accompanied by a failure of the concrete in tension. The creation of buckling stresses is greatly reduced by the provision of proper room for expansion through the use of expansion joints at intervals.

The kind of failure to be feared most in concrete pavements is excessive cracking, which can only be produced through a failure of the concrete in tension due either to direct forces, or to bending. Of the two,

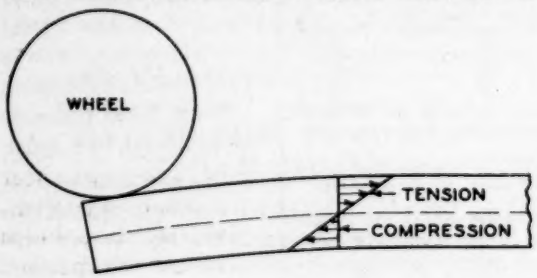

FIG. 1A

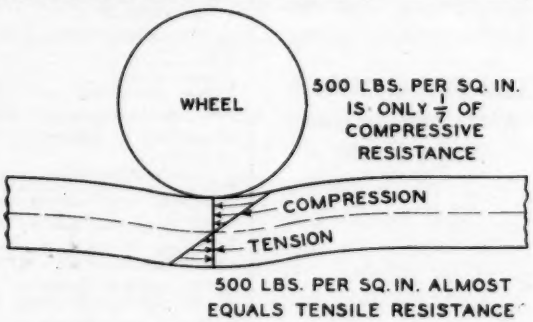
WHEEL
500 LBS. PER SQ. IN. IS ONLY 1/7 OF COMPRESSIVE RESISTANCE
COMPRESSION
TENSION
500 LBS. PER SQ. IN. ALMOST EQUALS TENSILE RESISTANCE

FIG. 1B

Bending Stresses Due to Wheel Loads—Showing that a Bending Failure of Concrete Always Results from a Failure of the Concrete in Tension

the bending effects of traffic and of other causes, such as subgrade settlement, are most important.

If the road is reinforced with steel the above statements are still valid, for the steel, as can be shown by analysis, does not become fully effective until after cracking takes place. Its function is primarily to prevent the cracks from spreading.

The integrity of a concrete road is thus seen to be largely dependent upon the resistance offered by the concrete to bending but there is one peculiarity about concrete road design which is not now fully realized by many engineers, namely, that under heavy frequent traffic the bending stresses very nearly approach the resistance of the concrete to repeated bending. In other words, concrete roads have a very small factor of safety against repeated bending stresses and even a slight lack of bending resistance may result in rapid cracking and a slight excess may greatly delay or even prevent excessive cracking. The very fact that it is economical to design concrete roads up to the very limit of safety as far as cross-bending resistance is concerned, shows very forcibly the importance of using a concrete having as high a bending resistance as possible. Such concrete will also have a sufficiently high compressive resistance but the converse is not always true. Many states have already recognized the bending test for concrete as being of very much greater significance than the compressive test and others are following.

The Bureau of Public Roads—New Jersey Test Results

The two materials which are compared in this test are both of very high quality in their respective types. The crushed stone is a trap rock of great hardness and toughness having a percentage of wear of 2.0. The gravel in the past has shown an abrasion loss of approximately 6 per cent in the Gravel Abrasion Test.* This percentage shows the gravel to be of high quality. It consists of rounded fragments of sandstone, quartz and rhyolite. The trap rock is extremely angular in shape, and, in consequence, the crushed stone has a higher percentage of voids than the gravel in samples having like mechanical analyses. Because of this fact, as pointed out by Mr. Jackson, the stone concrete showed a lower yield than the gravel concrete, per bag of cement, when identical arbitrary proportions, such as 1:1¾:3½, are used. In the stone concrete more of the mortar is required to fill the voids than in the gravel concrete and less of it is available for spreading the stone. The tests show that at 28 days, in the 1:1¾:3½ concrete, the stone concrete averaged 12.8 per cent higher in modulus of rupture than the gravel concrete, and at 6 months was still higher to the extent of 13.2 per cent, an average of approximately 13 per cent. The compressive strengths of the stone and gravel concrete at 28 days and 6 months were practically identical and both were of high value.

In the mixes in which the ratio of sand to coarse aggregate was 33:67, 36:64 and 40:60, the average modulus of rupture of the stone concrete was still considerably higher than that of the gravel concrete. The important point to notice, however, is that in 49 of the 52 comparisons for modulus of rupture, the stone tested higher than the gravel and averaged 12 per cent higher. The gradings of coarse aggregates used covered a wide range including those acceptable and those not acceptable to the state. The results could hardly be more conclusive for the particular materials tested.

It has been demonstrated, in connection with the two particular coarse aggregates under test, that the characteristics of the coarse aggregate have a decided influence on the cross-breaking strength of concrete. The difference in cross-breaking strengths, amounting to 12 per cent, is such that a gravel slab should be 6 per cent greater in thickness than a stone slab, or approximately ½ inch more gravel concrete should be required to produce the same slab strength that will result from the use of stone concrete.

It is well to again emphasize the influence which the modulus of rupture of concrete has on the life of a concrete pavement. It has been generally accepted, as the result of extensive field and laboratory investigations, that a concrete road should be designed by the use of the following formula:

$$D = \sqrt{\frac{3W}{S}}$$

Where D = Thickness of the slab at the edge
W = Maximum wheel load to be applied
S = One-half the modulus of rupture

The value for S is taken at ½ the modulus of rupture because laboratory tests have shown that if the working stress S exceeds approximately 55 per cent of the modulus of rupture, the concrete will fail in a comparatively few applications of load due to fatigue, while if the stress is kept below that figure the load may be applied millions of times and fatigue is long delayed.

*Bulletin 1216, U. S. Department of Agriculture.

Let it be assumed that the modulus of rupture of the concrete is equal to the average value of the stone concrete at 28 days, namely, 570 pounds per square inch. The working stress would then be 285 pounds per square inch for use in the above formula. The modulus of rupture of the gravel concrete was only 505 pounds per square inch at 28 days and a stress of 285 pounds per square inch is 56.3 per cent of this modulus of rupture while the same stress of 285 pounds per square inch is only 50 per cent of the modulus of rupture of the stone concrete. As 55 per cent of the modulus of rupture seems to approximate the "dead line" beyond which the stress should not extend to prevent fatigue, it is well demonstrated how very important seemingly slight differences in modulus of rupture in concrete can be. The above assumed gravel concrete road having the same thickness as the stone concrete road is apt to be unsafe against cracking due to fatigue while the stone concrete road should remain uncracked. This is simply another way of stating that the fatigue limit of this particular gravel concrete will be reached sooner than the fatigue limit of the stone concrete because of its lower modulus of rupture.

It is entirely logical, therefore, that one of two things be done to improve the strength of the gravel concrete road: (1) Increase its thickness so that its bending stresses will be decreased to a value not in excess of 50 per cent of its modulus of rupture. (2) Change the proportions of the gravel concrete, requiring more cement so as to increase its modulus of rupture. The Bureau of Public Roads-New Jersey Tests do not show what change in proportions might be made in the gravel concrete to make it of equal cross-bending strength as the stone concrete although they do give an answer to the question of how much extra thickness of gravel concrete is necessary to make it of the same slab strength when crushed stone is used.

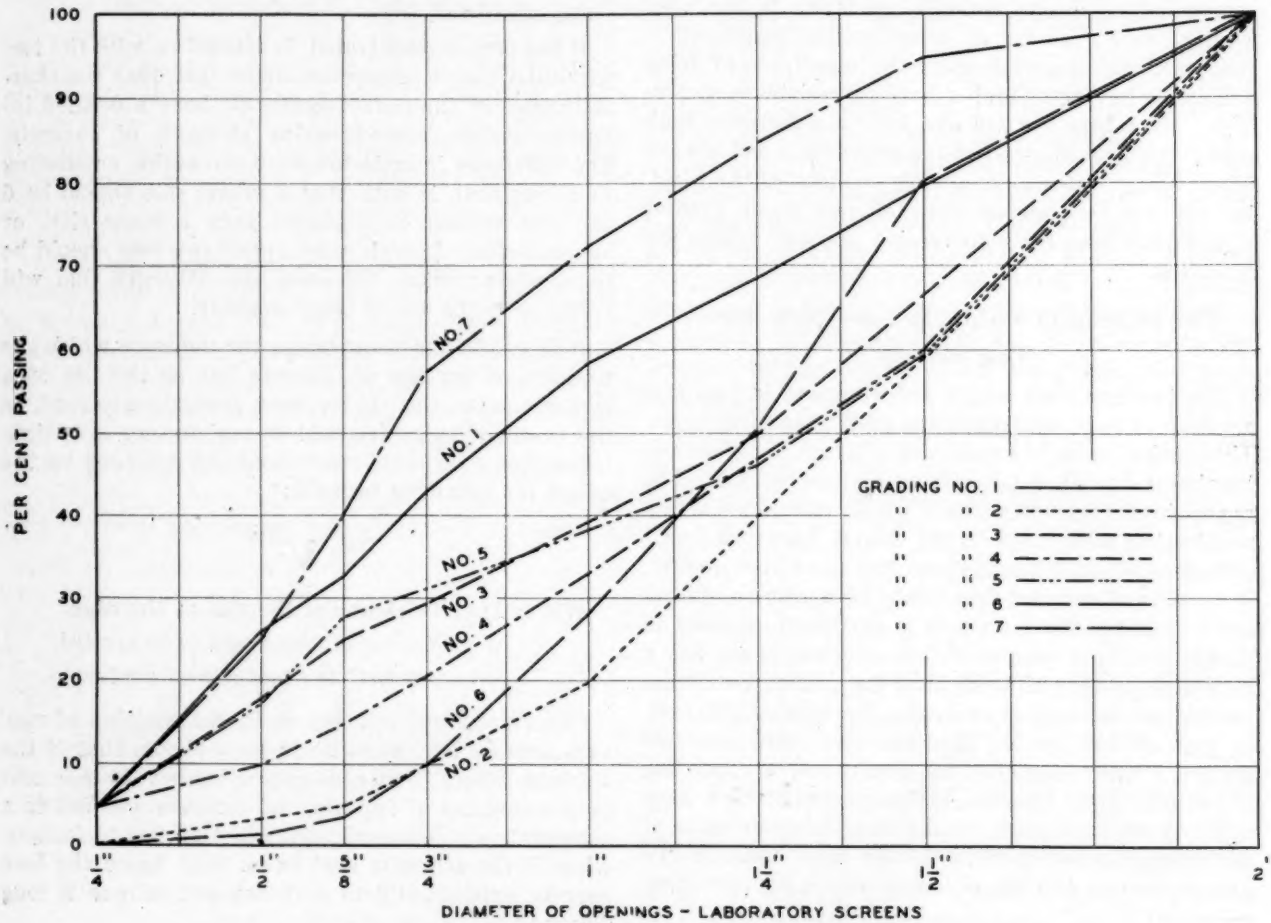

Fig. 2—Mechanical Analyses of Coarse Aggregates used in Bound Brook Tests

Bound Brook Tests

In order to get an answer to the second question, namely, that of what proportions of gravel concrete will give approximately the same cross-bending resistance as given proportions of stone concrete, the writer directed a short series of tests at the plant of one of the stone producers of New Jersey at Bound Brook. Identically the same coarse aggregates were used in these tests as in the Bureau of Public Roads-New Jersey State Highway Department Tests but, in addition, there were also included a sample of dolomite of very high grade and also a sample of gravel of very low resistance to wear in the Gravel Abrasion Test, approximating 25 to 30 per cent loss. Concrete was made from these respective coarse aggregates using the same fine aggregate in all cases. The proportions and the gradation of the coarse aggregates were varied and the concrete mixes were designed to produce concrete having pre-determined amounts of cement per cubic yard. In some cases the proportions were made on the basis of dry, rodded volumes according to A. S. T. M. methods for determining weight per cubic foot, and, in other cases, the proportions were in terms of loose volume. Beams were made 6 inches in cross-section and 30 inches long and were broken as cantilevers at the end of 14 and 28 days. The aggregate gradations used are shown graphically in Figure 2. These gradations were purposely made to cover the range of gradings permitted by the New Jersey State Highway Department specifications. Crushing strength tests were also made on the pieces resulting from the beam tests. In general, all of the aggregates show high compressive strength irrespective of quality or type. The differences in crushing strength are not significant and all crushing strengths were well above those ordinarily required for concrete roads. The cross-bending strengths were quite different in value, depending upon the coarse aggregates as shown in Table 1. The trap rock and dolomite are grouped together. The so-called concrete gravel having per per cent wear is placed in the middle group and the ¾-inch gravel, having 25 to 30 per cent wear, in the bottom group. It is quite striking that the modulus of rupture of the stone concrete is much higher than of the gravel concrete and very much higher than the ¾-inch, or poor gravel, concrete.

Each result is the average of three cross-bending tests. Comparison of individual mixes is probably not warranted in these tests but the average results are significant. It is to be noted that, although the stone concretes tested had an average cement content of only 6.1 bags per cubic yard as against 6.21 and 6.40 for the good gravel and poor gravel respectively, the modulus of rupture of the stone concrete was 53 pounds, or 8.4 per cent higher than the gravel concrete, and 130 pounds or 23.5 per cent higher than the poor gravel concrete. In other words, the stone concrete had a higher modulus of rupture than the gravel concrete even with a smaller content of cement per cubic yard. These tests in their general results corroborate the Bu-

TABLE I.
BOUND BROOK TESTS

Mix No.	Proportions	Bags	Grading	Method	28 Day Tests: Compressive strength lbs. per sq. in.	28 Day Tests: Modulus of rupture lbs. per sq. in.
STONE (Trap rock and dolomite)						
27	1:1.70:3.67	6.0	5	A.S.T.M.	2866	560
11	1:1.78:3.67	6.0	4	"	3127	639
14	1:2:4	5.6	4	"	3883	650
12	1:1.74:3.67	6.0	4	"	3453	666
20	1:1.75:3.5	6.17	4	"	3343	678
4	1:1.79:3.5	6.3	2	"	3340	683
26	1:1.53:3.5	6.3	5	"	3516	684
6	1:1.65:3.5	6.3	4	"	3750	695
1	1:1.67:3.5	6.3	1	"	4141	708
28	1:1.76:3.5	6.3	6	"	3212	712
5	1:1.64:3.5	6.3	3	"	3786	712
15	1:2:4	5.56	4	"	4230	727
8	1:1.56:3.5	6.3	4	"	3433	770
	Average	6.1			Average 3544	Average 683
CONCRETE GRAVEL (6% wear, Gravel Abrasion Test)						
2	1:1.36:3.5	6.3	1	A.S.T.M.	3995	592
7	1:1.23:3.5	6.3	4	"	3718	609
16	1:1.75:3.5	5.87	4	"	3373	621
25	1:1.23:3.5	6.3	5	"	3940	652
3	1:1.38:3.5	6.3	2	"	3940	672
	Average	6.21			Average 3793	Average 629
¾-INCH GRAVEL (25 to 30% wear, Gravel Abrasion Test)						
10	1:1.15:3.5	6.3	7	A.S.T.M.	3201	495
19	1:1.5:3	6.48	7	"	3866	518
18	1:1.75:3.5	5.82	7	"	3767	593
13	1:0.85:3.15	7.0	7	"	4600	603
	Average	6.40			Average 3878	Average 552

COMPARISON OF AVERAGE VALUES FOR MODULUS OF RUPTURE AT 28 DAYS (A. S. T. M. METHODS)

Type of aggregate	Modulus of rupture	Cement Content, bags	Bags of Cement per 100 lbs. modulus of rupture	Ratio	Probable No. bags of cement required for equal modulus of rupture
Stone	683	6.10	0.892	1.00	6.0
Concrete Gravel	629	6.21	0.985	1.10	6.6
¾-Inch Gravel	552	6.40	1.16	1.30	7.8

COMPARISON OF AVERAGE VALUES FOR COMPRESSIVE STRENGTH AT 28 DAYS (A. S. T. M. METHODS)

Type of Aggregate	Compressive strength	Cement content, bags	Bags of cement per 1,000 lbs. compressive strength	Probable ratio of cement required for equal compressive strengths
Stone	3544	6.10	1.72	1.05
Concrete Gravel	3793	6.21	1.64	1.00
¾-Inch Gravel	3878	6.40	1.65	1.00

Fig. 3—Crushed Stone Concrete (stone has 2.0 per cent wear). The rough angular faces have bonded sufficiently well with the mortar to break much of the stone in spite of its great hardness and toughness.

reau of Public Roads-New Jersey State Highway Department Tests but they go further in showing that a change of proportions is warranted to produce road slabs of equal strength. They show that more cement is required in the gravel concrete than in the stone concrete instead of less cement as required by the time-honored arbitrary proportion method in which the proportions are stated as 1:1¾:3½, etc. The probabilities are, judging from the results obtained, that 10 per cent more cement is necessary in the gravel concrete of high quality than in the crushed stone concrete and perhaps as much as 30 per cent more cement should be used in the concrete containing the poor gravel than in that containing the crushed stone in order that the slab strengths may be alike in all cases. The Bound Brook tests show that there is no basis for adhering to the same proportions of mortar when changing the proportions of concrete to suit different coarse aggregates, for it is shown that the stone concrete is stronger than the gravel concrete even though its mortar is leaner. It may be well in fact to add to the sand content of the stone concrete and decrease it in the gravel concrete to make for workability in the former and prevent over-sanding in the latter.

No doubt the differences in cross-breaking results in part are due to the shape of the fragments, to the roughness of their surfaces, and to the strength of the fragments. It seems entirely reasonable that smoothness of surface must have influence on the cross-breaking resistance of concrete, because the adhesion of the mortar to the surface is probably aided when the surfaces of the coarse aggregates are rough in much the same way as the bond resistance is increased mechanically in a deformed reinforcing bar as compared with a smooth reinforcing bar. It also seems reasonable that angularity of particle may be of some assistance in creating higher tensile resistance because of the greater interlocking effect thereby produced. The strength of the fragments probably also has influence because the fragments are placed in tension. At any rate, in the broken cross-bending specimens it was noticeable that there was better bond between the stone and the mortar than between the smooth gravel and the mortar, as indicated by the fact that few of the gravel particles were broken. On the other hand, there were more fragments broken in the soft gravel specimens than occurred in beams containing the gravel of high quality. These indications are somewhat imperfectly illustrated in Figures 3, 4 and 5.

Minnesota Tests

Some light is thrown on the question of influence of shape of particle and characteristics of surface by tests recently published in the March, 1928 issue of Concrete by F. C. Lang, Engineer of Tests and Inspection, Minnesota Department of Highways. A diagram

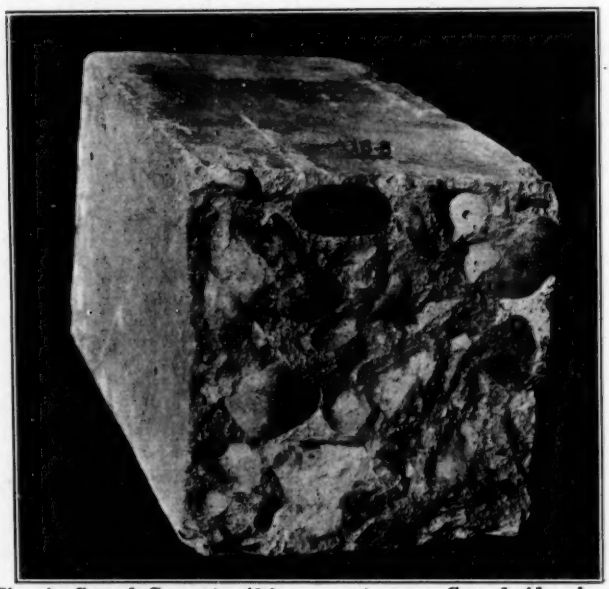

Fig. 4—Gravel Concrete (6.0 per cent wear, Gravel Abrasion Test). Mortar bond not sufficient to break the smooth, rounded, hard fragments. The broken fragments are composed entirely of soft, weak materials.

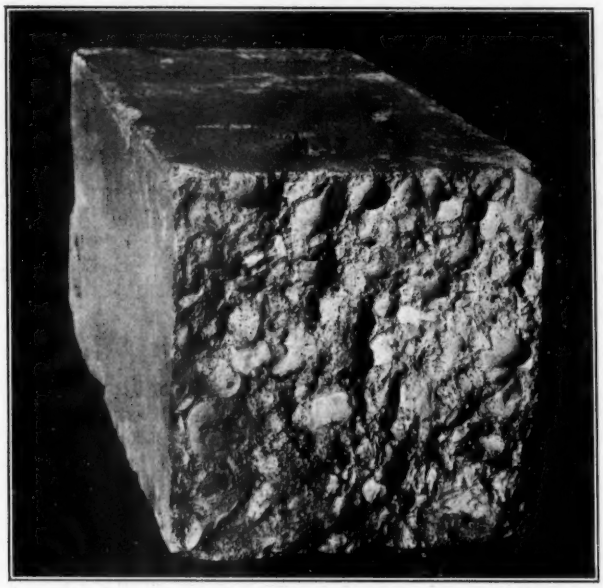

Fig. 5—Gravel Concrete 25.0 to 30.0 per cent wear, Gravel Abrasion Test). The harder, rounded, smooth fragments have released their bond with the mortar; the softer fragments have broken.

of the results reproduced from Mr. Lang's article is shown in Figure 6. In these tests the aggregates compared were as follows:

No. 1. A smooth water-worn gravel largely composed of igneous rocks from northern Minnesota. All flat, elongated and broken pieces were picked out by hand.

No. 2. An ordinary commercial gravel containing crushed oversize from St. Paul, Minn.

No. 3. A crushed limestone.

No. 4. A crushed trap rock.

No. 5. A crushed sandstone. Per cent loss in abrasion test, 11.1. One-half hour absorption, 3.13 per cent.

The tests were made using a constant water-cement ratio. It is apparent that the angularity or smoothness of surface, or perhaps their combination, have influenced the cross-breaking resistance of the concrete. Both the limestone and the trap rock have a higher modulus of rupture than the rounded smooth gravel, to the extent of approximately 23 per cent in the case of the trap rock and over 11 per cent in the case of the limestone. When compared with the commercial gravel containing, in part, crushed particles having rough and angular surfaces, the differences in cross-breaking strength were not so apparent. These tests,

Continued on page 26

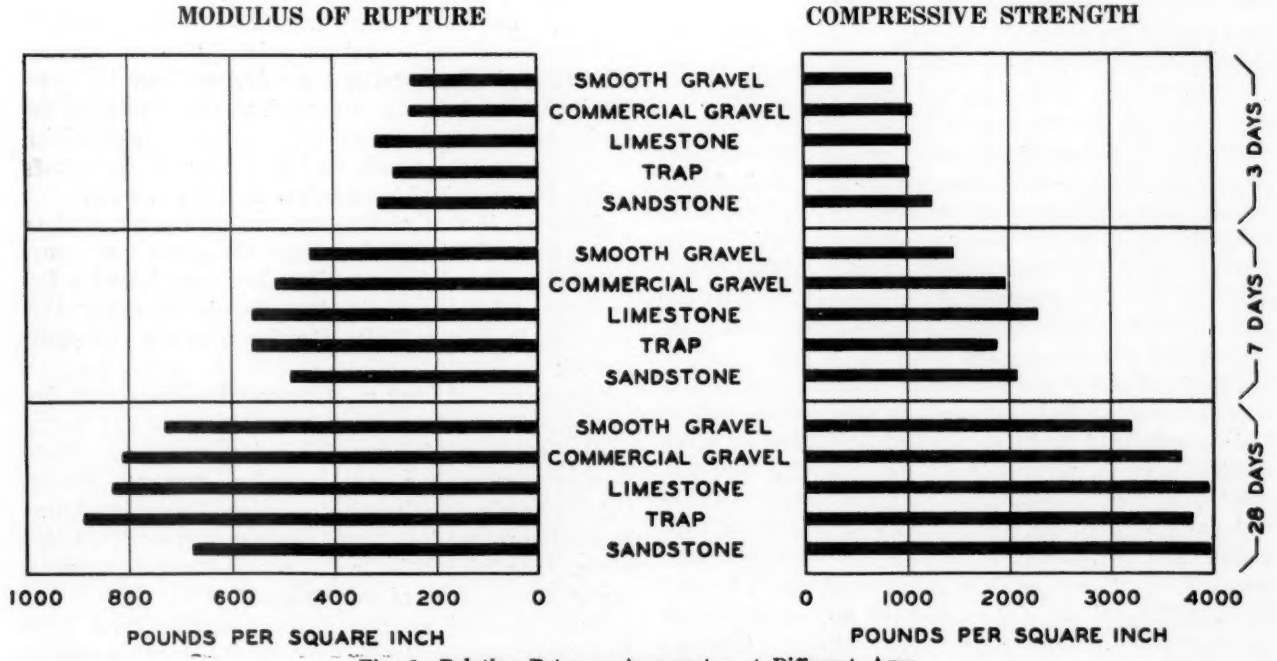

Fig. 6—Relation Between Aggregates at Different Ages

Redrawn from Figure 1 in F. C. Lang's paper, "Effect of Shape and Character of Coarse Aggregate on Strength of Concrete" published in March, 1928, issue of "Concrete"

Research the Life of Industry[1]

It Keeps Production Machinery in Motion, Finding New Uses for Output, Utilizing Waste, and Evolving Substitutes

UNTIL a few years ago the function of research was generally limited to the development of discoveries which would form the basis of entirely new industries. The changes which the World War made in industry brought a new conception of the importance of industrial research in keeping the machinery of production in motion. Mass production, elimination of waste, hand-to-mouth buying, and other successful features of American industry which have been developed since the war have become possible on account of the research work in the post-war problems of reorganization.

Industrial research is handled in three distinct ways. First, by an individual corporation which has set up its own research department to develop its product a little ahead of its competitors. Research, however, is costly and some industries have met the problem of maintaining laboratory and field work by trade associations. This is the second method which has been employed to keep research activities flourishing.

Bureau of Standards

The third method for employing research is the use of governmental and institutional facilities. In recent years the Bureau of Standards at Washington has been expanding its usefulness as a laboratory for industrial research. Any manufacturer or producer having research problems to work out may use the facilities of the Bureau, and this work has been especially helpful in making tests of new devices and new materials. The Bureau has made reports on a number of basic commodities, and has determined the specifications necessary for high quality in such things as varnishes, door hinges and gasoline pumps.

Founded in 1901, the Bureau of Standards today is a large institution like a university with a total staff of 785 experts and technicians, and a library of some 27,000 books in several languages. During the last fiscal year the Bureau made approximately 180,000 tests at an operating cost of $2,000,000. It is estimated that the Bureau saves the United States Government about one hundred million dollars each year by scientific analysis of the goods the government buys, ranging from thumb-tacks to battleships. Colleges and privately endowed institutions also carry on research which is of direct benefit to industry. Most of the work undertaken in these laboratories, however, is intended for future benefit rather than for immediate needs.

An Outstanding Example

The outstanding example of a corporation based upon research is the E. I. du Pont de Nemours & Co., Inc., of Wilmington, Delaware. The war left this company with an expanded production which had been devoted to supplying the explosives needed in the prosecution of the war. Through the application of research the company transformed a possible calamity into an opportunity. The manufacture of explosives is primarily a chemical industry, and it remained for the company to make use of the need for dye stuffs formerly supplied by Germany. According to the Tariff Commission, the dye industry in the United States last year supplied 93 per cent of the domestic consumption, whereas in 1913 only 13 per cent of the dyes consumed here were produced in this country.

In the manufacture of explosives nitrocellulose is developed and used. Rayon, paint, imitation leather, celluloid and other products are derived from this useful chemical substance. Research was conducted by the du Ponts which revolutionized the use of paint, which in turn developed a new usefulness for the dye stuffs which formerly had gone primarily into textiles.

Research is now playing its part in the recovery of the meat-packing industry from the seven lean years after the war. In announcing the formation of a Department of Research in Armour and Company this summer, F. Edson White, President of the Company, stated:

"Business is taking on a more scientific aspect day by day. Research work is developing new and better methods and making possible better products. Many leading corporations have organized research departments and given to them broad latitude of action. There is nothing mysterious about the research work we plan to do. The job will be to dig out essential facts relating to the conduct of our business."

Raw material producers in particular have been forced by the situation in their market to give greater attention to research. This may be seen from the con-

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[1]Reprinted from the Manufacturers Association Bulletin, December, 1927.

The President's Page

AFTER an exhaustive search of various possible locations, we have fortunately secured splendid quarters for our laboratory. The building which will house our new undertaking is located fairly centrally, on the corner of 14th and S Sts., N. W., and is easily accessible from all points of the city. The structure itself is rather imposing in appearance, and we have secured a room on the second floor front 100 feet long and 30 feet wide. Through the center will be constructed a main partition dividing the room approximately into half, one side for the laboratory equipment and the other to be subdivided into various offices, thus enabling us to combine our executive offices with the laboratory. Such an arrangement is highly desirable, as it will conserve the time of our Director of Engineering in enabling him to attend to his office duties and yet be in close touch with the research being conducted in the laboratory. The offices will be five in number, with a total floor area considerably in excess of that we now have in the Earle Building. In the basement of the same building we have secured sufficient space to store materials, install the necessary screens and care for the mixing of concrete, using the main laboratory only for actual testing. The whole lay-out is not only comfortable and efficient, but is pleasing and even impressive in appearance. The laboratory and offices will give the appearance of being that sort of place in which exact and precise work would naturally be done.

Needless to say, we are purchasing only the finest equipment for the laboratory that can be secured. It will not be possible to throw doubt successfully on the conclusions reached by endeavoring to cast suspicion on the accuracy of the equipment used. We are securing not only reliable apparatus, but the most advanced and efficient of its kind. We may not fully equip the laboratory immediately, but all the apparatus which is installed will be the best procurable.

Fortunately—and this was one of the considerations which prompted us to take the space—the total rent for offices, laboratory, and basement will not exceed that which we would be required to pay this year for our offices alone if we remained in our present location.

Our address in the Earle Building will remain unchanged for some two months, during which period of time we will install the equipment for the laboratory, and the landlord will erect the necessary partitions and make other changes required by us.

To prosecute properly the research work, which will be started just as soon as possible, we will require, in addition to our present staff, the services of a laboratory engineer, an assistant, and a laborer, whose total salaries will amount to about $5,000 annually. The men for these places have already been selected with discriminating care.

There is every reason to believe that with adequate equipment, and skillful assistance guided and directed by the profound knowledge and wide experience of our Director of Engineering in matters relating to testing materials, the laboratory of this Association will soon enjoy a high reputation. We believe that with such a laboratory at his disposal the results which can be obtained will be beneficial to highway-building agencies, to the public at large, to the industry and especially to our own members. We have an unparalleled opportunity for advancement and a program of useful service about which the industry can rally and which it should loyally support.

* * * * * * *

OUR budget for the present year has been carefully itemized and appropriations made for each phase of our activities on the lowest possible basis consistent with their effective conduct. We propose to live within our income, but additional revenue could be expended to marked advantage.

* * * * * * *

WE should secure new members, thereby strengthening the Association morally and financially. We should not find it necessary to make extended explanations to potential members, as with such facilities at the disposal of the Association, every crushed stone producer should feel that membership in the Association is an apportunity rather than a duty. In no better way can any of use serve the Association than by securing new members. We earnestly ask that the advantages of membership in the Association be vigorously called to the attention of every producer who is not now a member, and that each of our present members accept as a responsibility and a pleasurable duty the securing of membership of producers in his territory who do not now enjoy that privilege.

* * * * * * *

THE contributions to the fund for establishing and equipping a laboratory have now slightly passed the

Continued on page 27

The Crushed Stone Journal

J. R. BOYD, Editor
A. T. GOLDBECK, Director, Bureau of Engineering
The National Crushed Stone Association

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Easton, Pa.
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*Deceased.

A Word to the Salesmen

Those of you who were fortunate enough to be present at the West Baden Convention will recall that during the Session for Salesmen the question of giving a wider distribution to our Engineering Bulletins was discussed. Many of the salesmen present pointed out the excellent results which had been obtained from distributing these Bulletins, and everyone agreed that a much wider distribution should be given to them during 1928. There are still a number of our member companies who evidently do not fully appreciate the excellent results to be obtained from placing these Bulletins in the hands of highway engineers, architects, contractors, state, county and township highway officials, and any others directly or indirectly interested in highway and building construction.

Copies of the Bulletins which have so far been published can still be obtained and we earnestly request that those who have not yet done so, immediately send in their orders to the Secretary's Office in Washington, designating the number and quantity of each Bulletin desired. Remember, the cost is only ten cents per copy and we are confident that for the slight expenditure involved the results will be exceedingly gratifying. The following Bulletins have been published to date:

No. 1—"The Bulking of Sand and Its Effect on Concrete."

No. 2—"Low Cost Improvement of Earth Roads With Crushed Stone."

No. 3—"The Water-Cement Specification for Concrete and Its Limitations."

Order Your Proceedings Immediately

The Proceedings of the Eleventh Annual Convention recently held at West Baden will shortly be ready for distribution, probably about April 15.

This volume will include all of the papers presented before the Convention as well as a ver batim report of all discussions and of the Annual Banquet. This is the only publication in which a complete history of the Eleventh Annual meeting can be obtained under one cover.

Each company should order a sufficient number of copies so as to place one in the hands of each of its executive officers, salesmen and superintendents. It would also be well worth while to send a copy of these Proceedings to state highway engineers as well as county and town highway officials. The information contained therein, representing the foremost thought of men who have attained distinction in the field of highway engineering would unquestionably be received most gladly.

Additional copies will be sold at the rate of $2.00 each and members are urgently requested to send their orders in immediately as the edition will no doubt be exhausted at an early date.

St. Louis Quarrymen's Association Elects Officers

Announcement was recently made by the St. Louis Quarrymen's Association of their election of officers for 1928 as follows:

President—Wm. Eyermann, Eyermann Construction Co., St. Louis, Mo.

Vice-President—Theodore Fehlig, Fehlig Construction Co., St. Louis, Mo.

Secretary-Treasurer—J. W. McCullough, Rock Hill Quarry & Construction Co., St. Louis, Mo.

Executive Secretary—E. J. McMahon, St. Louis, Mo.

Increasing Our Membership

The problem of increasing membership in the Association is an ever-present one and cannot be considered as solved until every eligible crushed stone producer in the United States and Canada has joined.

How can this goal most quickly and effectively be reached? This is a question which has been giving real concern to your executive officers and merits the serious attention of every member of the Association. Undoubtedly each member knows of some producer in his territory who has not joined the Association. This is a condition which should not be allowed to con-

tinue and which can best be corrected through the personal efforts of our members.

The Secretary's Office is constantly in correspondence with these prospective members, but the letter has yet to be formulated which carries the weight and conviction of a personal interview. Give these non-members first hand information as to the many ways in which the Association can be of service to them. The establishment of our Research Laboratory, which will be actively operating within the next two months, will materially increase the effectiveness of the service which the Association can render to its members and to the industry.

The results of the work of the Membership Committee, the personnel of which is given elsewhere in this issue, will be very materially increased if supplemented by the individual efforts of each of our members. Through cooperation of everyone there is no doubt but that a decided enlargement of our membership can be reported at the next convention.

President Graves Appoints Committees

President Graves has just announced the appointment of the following committees for 1928.

Executive Committee

Otho M. Graves, Chairman, General Crushed Stone Co., Easton, Pennsylvania.
W. M. Andrews, Lake Erie Limestone Co., Youngstown, Ohio.
H. E. Bair, The France Stone Co., Toledo, Ohio.
C. M. Doolittle, Canada Crushed Stone Corporation, Ltd., Hamilton, Ont., Canada.
E. J. Krause, Columbia Quarry Co., St. Louis, Mo.
W. L. Sporborg, Rock-Cut Stone Co., Syracuse, N. Y.
A. L. Worthen, Connecticut Quarries Company, Inc., New Haven, Conn.

Research Committee

John W. Stull, Chairman, Liberty Lime and Stone Co., Rocky Point, Va.
A. H. Bannister, Brownell Improvement Co., Chicago, Ill.
L. C. Bonnell, F. R. Upton, Inc., Newark, N. J.
C. E. Glassen, Columbia Quarry Company, Columbia, Ill.
A. T. Goldbeck, Nata'l Crushed Stone Assn., Washington, D. C.
Stanley M. Hands, River Products Co., Iowa City, Iowa.
Ross G. L. Harstone, Canada Crushed Stone Corp., Ltd., Toronto, Ontario, Canada.
Herbert F. Kriege, The France Stone Co., Toledo, Ohio.
George E. Martin, The Barrett Company, New York City.
F. C. McKee, West Penn Cement Company, Pittsburgh, Pa.
Clarence A. Munson, New Haven Trap Rock Co., New Haven, Conn.
Paul B. Reinhold, Reinhold and Company, Pittsburgh, Pa.
E. O. Rhodes, American Tar Products Co., Pittsburgh, Pa.
A. B. Rodes, Franklin Limestone Co., Nashville, Tenn.
W. R. Sanborn, Lehigh Stone Co., Kankakee, Ill.
George E. Schaefer, General Crushed Stone Co., Rochester, N.Y.
T. I. Weston, The Weston and Brooker Co., Columbia, S. C.
A. J. Wilson, Granite Rock Co., Watsonville, Calif.
W. F. Wise, Texas Trap Rock Corp., San Antonio, Texas.

Committee for Selection of Association Insignia

A. T. Goldbeck, Chairman, Nat'l Crushed Stone Assn., Washington, D. C.
C. M. Doolittle, Canada Crushed Stone Corp., Hamilton, Ont., Canada.
N. C. Rockwood, Rock Products, Chicago, Ill.

Membership Committee

J. R. Boyd, Chairman, National Crushed Stone Association, Washington, D. C.
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H. E. Hopkins, Cement, Mill and Quarry, Chicago, Ill.
E. G. Lewis, The Bucyrus-Erie Company, New York City.
H. W. Munday, Pit and Quarry, Chicago, Ill.
N. C. Rockwood, Rock Products, Chicago, Ill.

Discussion of the Bureau of Public Roads—New Jersey Tests

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however, corroborate in a general way the tests previously cited and certainly show that shape of particle and smoothness of particle have influence on the cross-breaking resistance of concrete. The sandstone had a low cross-breaking resistance but it was a sandstone of very poor quality as determined by the Deval Abrasion Test. Practically no states will allow a stone having a Deval Abrasion loss in excess of 7 per cent to be used as a coarse aggregate in concrete road construction, whereas, the sandstone tested had an abrasion loss of 11.1 per cent. Apparently, then the quality of the aggregate, as determined by the abrasion test, influenced the cross-breaking resistance of the concrete and the indications are also very strong that in the Bound Brook, New Jersey, tests previously cited, the same remark might be made with respect to the two gravels tested. The gravel having 25 to 30 per cent loss was much lower in cross-breaking strength than the gravel having only 6 per cent loss and this was true notwithstanding the fact that more cement was used per cubic yard with the poor gravel than with the good gravel. The comparison unfortunately is somewhat clouded because the soft gravel was also smaller in size.

It should not be inferred from the above cited tests that all crushed stone will invariably test higher in cross-breaking strength than all gravel. The Minnesota crushed sandstone illustrates this point. It is very well demonstrated, however, that all coarse aggregates do not produce concrete having like concrete road making qualities and it is thoroughly shown that it is not safe to proceed on that assumption in using aggregates in concrete roads.

When a concrete road is built of a given thickness it is assumed that it is capable of carrying a wheel load of a given maximum weight. As pointed out, the factor of safety of a concrete road, of necessity and for the sake of economy, must necessarily be made low. As a result, concretes having a comparatively low modulus of rupture are apt to fail while concretes having a high modulus of rupture may be perfectly satisfactory. In the light of our present knowledge the logical procedure is to recognize these differences in coarse aggregates and by means of cross-breaking tests determine what changes in proportions should be made or what changes in road design should be required so that road slabs might have equal capacity for carrying the maximum loads for which they are intended.

Research the Life of Industry

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sequences of events in recent years which have materially affected the markets for rubber, sugar, cotton, oil and coal.

What Might Have Been

When the British Government established the Stevenson policy of restricting the output of rubber from the British plantations, the American market was violently shaken. Research undertaken earlier might have overcome the embarrassment caused rubber manufacturers in this country by the British action. Little attention had been paid to new sources of supply for rubber until that moment, nor had sufficient support been given to the development of synthetic rubber until then. Although the production of rubber produced by chemical synthesis is as yet incapable of competing with the natural product, no scientist will admit that such an eventuality is impossible.

The sugar industry has been another one to neglect adequate research until the approach of a depression which was caused by the development of new sources of supply. Beet sugar and corn sugar production enter directly into competition with cane sugar. One of the great wastes of the cane sugar industry has been the failure to utilize by-products to the fullest extent. Approximately 85 per cent of sugar cane is available for by-product uses. The waste of molasses offers a potential source of supply for motor fuel. At present the residue of molasses is utilized as a valuable agricultural product for feeding cattle. For years the cane waste was found of no further use than as fuel to run the sugar mills. A recent discovery makes possible the use of the waste cane pulp for the manufacture of a lumber substitute.

The lumber industry, producing about 90 billion feet annually, has been threatened by the new competition through the use of these substitutes. Research, however, is aiding the lumber industry by finding new uses for the waste sawdust, such as the making of linoleum, dynamite and Bakelite. The Bakelite Corporation is another separate industry which conceived in the research laboratory a superior insulation for electricity and by the aid of research extended the uses of its product to almost every line of industrial activity.

Remarkable progress has been made by the gas industry which a few years ago was confronted with the necessity of finding new markets and developing new technique to reduce the cost of production. A fund of $100,000 a year was appropriated to conduct

a five-year research program. The result was the development of gas refrigeration and more efficient gas cooking-stoves which could compete with electric appliances.

Insurance Against Disaster

The ever present possibility of the discovery of new materials by chemical synthesis forces the recognition of research as the best insurance against disaster. The past year has witnessed a revolutionary change in the production of alcohol where the cheaper and superior synthetic product has made the old method of distillation from wood and grains or syrups archaic.

As a result of research in the costs of production, the textile industry has reorganized not only its methods of manufacture, but has transferred the center of activity from New England to the South, the source of supply. The introduction of artificial silk which is virtually as cheap as cotton forced the cotton textile industry to put its own house in order to meet the new competition. The development of a style demand, emphasizing the smart appearance of cotton textiles, stimulated the market. A study of costs and their allocation is operating towards greater economy.

The problem of how much to spend on research is a difficult one to answer. No amount seemingly would be too great when the results are measured in comparison with what has already been accomplished. The difference between earnings of two corporations in the same competitive field can be partly traced to the amount of research conducted by each.

The recovery of the Chilean nitrate industry, which contributes substantially to the revenue of the Chilean Government, must also be attributed to research. The production of synthetic nitrate—research again—in Germany was beginning to cut sharply into the market for the Chilean product. The development of the Guggenheim process made possible an extraction of Chilean nitrate which is estimated to be about 50 per cent more efficient and more economical than the old method.

President's Page

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$20,000 mark. We should have at least $25,000. Some of our members who have not subscribed surely intend to do so. Now is the time to act. The full amount of the subscription need not be paid at once and can be paid in three installments at intervals of three months if so desired. All contributions are welcome and helpful, whether for $50, $500 or $1,000. Our executive offices, the Bureau of Engineering, and the laboratory are being capably and efficiently managed and deserve our hearty and loyal support. We have set our hands to the plow and we must not turn back until the work is done. If you, in reading this, realize that you have intended to subscribe to the laboratory fund, but have been merely putting it off, won't you do it now? Just write a brief note stating how much you will subscribe and mail it either to the office of the President in Easton or to that of the Secretary in Washington.

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